PHD

# Tacit Knowledge Transfer in Inter-Organisational Networks
## A social network analysis of Formula 1

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# Tacit Knowledge Transfer in Inter-Organisational Networks:

A social network analysis of Formula 1

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# Abstract

Inter-organisational networks of businesses such as Formula 1, information management systems, pharmaceutical industries, and aerospace manufacturers face challenges in for technological development, competition, and logistics. In such businesses firms form alliances with their competitors to tackle specific projects, expand their resource base, and overcome regulatory changes. Researchers have identified these conditions as ideal for fostering explicit and tacit knowledge transfer and the network as a source of competitive advantage.

This study finds that it is networked individuals with high tacit knowledge content that are source of competitive advantage in such inter-organisational networks. These networked individuals impact organisational performance and alter the competitive balance within the network.

The research is situated within the context of Formula 1. The business model of Formula 1 involves trading and selling both technology and human resource with the competitors and reflects the important role played by tacit knowledge in this process. Formula 1 is an ideal context for this research as the grand prix industry is a fast clockspeed and small world ecosystem with organisations producing the same product i.e. the grand prix car. Formula 1 teams innovate and respond to external challenges such as regulation changes via movement of networked individuals. These individuals introduce novel knowledge within the organisation, and play different managerial and technical roles.

This research establishes other contextual factors that affect tacit knowledge transfer in Formula 1. The role of an individual in an organisation is salient when considering the effect of that individual on team performance. Individuals in technical and managerial roles affect performance to a greater degree than drivers. Regulation changes are key drivers of technological discontinuities in Formula 1, and the movement of networked individuals plays an important role in teams' ability to respond to these regulation changes.

The research findings are particularly relevant for industries that share Formula 1's technological and competitive context such as pharmaceutical, aerospace, and information management industries.

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# List of Abbreviations

| | |
|---|---|
| BRM | British Racing Motors |
| BMEP | Brake Mean Effective Pressure |
| B/S | Bore to Stroke Ratio |
| CEO | Chief Executive Offices |
| DFV | Double Four Valve |
| DFL | Double Four Valve Long Distance |
| DOHC | Double Overhead Camshaft |
| EC | Combustion Efficiency |
| EV | Volumetric Efficiency |
| FIA | Fédération Internationale de l'Automobile |
| FVA | Four Valve Type A |
| FW | Frank Williams |
| HANS | Head and Neck Support |
| HP | Horsepower |
| MP4 | McLaren Project 4 |
| RPM | Revolutions Per Minute |
| R&D | Research and Development |
| SCA | Single Camshaft Type A |
| V/C | Valve per Cylinder |

# Chapter 1. Introduction

A rise in interdependencies between firms and technological progress of recent decades has brought knowledge transfer in inter-organisational networks to the centre stage (Ahammad et al., 2016; Smith et al., 2007). Interconnectivity and rapid change has meant that people must share their knowledge pool with others, and learn from them (Szulanski et al., 2016; Stauffer, 1999). Knowledge transfer is essentially an innovation process (Fores, 2016; Robbins and Milliken, 1978) and the ability to innovate is a core capability in businesses (Iyer et al., 2017; McEvily et al., 2004).

Knowledge-intensive businesses, such as pharmaceutical, aerospace, and the automotive industry show superior innovation competence compared to other businesses. Innovation in these businesses is driven by various types of knowledge interaction and is result of 'knowledge dissemination and application' leading to improvement in firm performance (Fores, 2016; Palacios-Marques et al., 2013; Lazzeretti and Capone; 2017).

Knowledge transfer can also be thought of as a process by which one firm is affected by the experience of another (Argote et al., 2000). It has been made more difficult by rapid and radical technological changes and competitive pressure (Griffin, 1997). This process is incentivized by lower costs involved in replicating knowledge than the original costs of creation (Winter, 1995). These factors act as driving forces for formation of strategic alliances (Parkhe, 1991; Szulanski, 1996; Szulanski et al., 2016; Lyles and Gudergan, 2006; Gomes-Casseres et al., 2006; Dyer and Singh, 1998). An organisation's structural position in an inter-organisational network of strategic alliances influences its opportunities and constraints (Borgatti et al., 2009; Burt, 1992).

Businesses and organisations have invested in various initiatives to help the process of knowledge transfer in inter-organisational network of strategic alliances. While this has proven to be modestly effective in disseminating codified and explicit knowledge; it does not deal effectively with unstructured and non-codified tacit knowledge (Smith et al., 2007; Dalkir and Beaulieu, 2017). Polanyi (1964, 1967) distinguished between tacit and explicit knowledge, and argued that 'explicit' knowledge can be articulated, codified and written down/stored in a media, and hence it can be; relatively easily transferred, 'tacit knowledge' can neither be easily articulated nor codified, even by an expert practitioner.

In fact, critical organisation knowledge often resides in tacit form (Boisot, 1998, Nonaka and Takechi, 1995). It is therefore important to understand tacit knowledge from an individual's point of view to be able to effectively design and implement knowledge management practices in an organisation (Dalkir and Beaulieu, 2017; Bock et al., 2005; Kelloway and Barling, 2000).

Movement of tacit knowledge is inherently connected to movement (and interaction among) of individuals within a network space (Deeds, 2003; Gupta and Govindarajan, 2000; Pfeffer and Sutton, 2000; Smith et al., 2007; Squire et al., 2009; Iyer et al., 2017). This interdependency between movement of individuals and knowledge transfer is highlighted by Smith et al. (2007) study in which they quote a participating manager, "*wherever the term 'knowledge' is used, you should substitute people."* This implies that key to understanding tacit knowledge transfer, and its impact on organisational performance is to understand movement of individuals.

Existing consensus in the literature is focused on the importance of the inter-organisational network and valuable, inimitable resources as a source of competitive advantage (Peteraf, 1993; Dyer and Singh, 1998; Lavie and Drori, 2012). However there is no clear criteria for what makes a resource valuable or imitable. There is also a dearth of studies in the literature exploring the role of individuals and impact of linkages between them in the context of tacit knowledge transfer in networks. This study fills that gap and contributes to knowledge by visualising the importance of linkages of individuals on an organisation's performance. At personal level, this research is motivated by author's academic background in engineering and knowledge management research and wider interest in fast clockspeed industries.

The framework for visualisation is developed using the social network analysis. It is a research methodology which has its roots in sociology. Over the years, social network analysis has evolved into an interdisciplinary methodology with the incorporation of mathematics and statistics. It can be best understood as a tool to map and analyse the social structure of nodes and their relationships (Freeman, 2004; Huber 2009; Leon et al., 2017; Moody, 2001; Wassermann and Faust, 1994). Recent years have seen a rise in number of social network studies (Monge and Contractor, 2003; Barabasi, 2003; Christakis and Fowler, 2009; Leon et al., 2017). Development of powerful computations tools for social network analysis (Agarwal et al., 2008; Lazer et al., 2009) have aided the application of social network analysis in different contexts to analyse and visualise networks.

This study uses network of teams participating in Formula 1 as the case study for developing the said framework. The framework produces a network graph which shows movement of individuals, their linkages, and the tacit knowledge within the inter-organisational network over the period, 1992 – 2010. This network graph is used to identify and analyse tacit knowledge transfer and its effect on organisational performance.

The proposed model also allows for self-validation using a dataset (Formula 1 data) and demonstrates that movement of highly networked individuals; those with *high metric values* in the Formula 1 network; is associated with superior team performance. This is a novel method of tacking tacit knowledge transfer and has implications for knowledge management and organisational performance. These conclusions challenge the consensus in literature which is centred on the utility of the network as a source of competitive advantage and focuses at organisational level (Dyer and Singh, 1998; Lavie and Drori, 2012; Haas and Stuebiger; 2017; Leischnig; 2014; Lazzeretti and Capone; 2017).

## 1.1.The Focus of the Investigation

This thesis explores impact of individuals, their linkages, and the tacit knowledge flowing through the linkages on organisational performance in inter-organisational networks. Specifically, the research is guided by the following question,

*Research Question: How can we demonstrate the effect of networked individuals with high tacit knowledge on organisational performance in inter-organisational networks?*

This study is focused on understanding tacit knowledge transfer taking place within inter-organisational networks and its impact on organisational performance. Tacit knowledge resides within individuals and to understand tacit knowledge transfer, it is necessary to establish the quality and characteristics of this relationship between the tacit knowledge transfer and movement of individuals. This study characterises individuals as conduits of tacit knowledge flows (see Chapter 5). This characterisation has allowed the study to identify, track, and understand the impact of the movement of individuals, and accompanying knowledge, on organisational performance within the network.

The findings from this study identify the individuals with high network-metric values have a positive effect on a team's performance. Different category of individuals, such as engineers, designers, and drivers, affect team performance to different extent. This supports the hypothesis that networked individuals affect tacit knowledge transfer and organisation performance, and social network analysis can be used to map tacit knowledge transfer in inter-organisational network. This study highlights tacit knowledge as an important component of organisational performance.

## 1.2. Background to the Research

This research is focused on the inter-organisational network of Formula 1 constructors and automotive manufacturers. Formula 1 provides an appropriate setting to apply social network analysis and other methodological tools to understand movement of individuals and its effect on tacit knowledge transfer.

Formula 1 is being increasingly used for management research (Castellucci and Ertug, 2010; Jenkins, 2010; Marino et al., 2015; Pinch et al., 2003). Formula 1 is an industry with yearly revenue of $16.2 billion (Sylt, 2015), employing over 50, 000 people in more than 30 countries (Jenkins et al., 2005). Formula 1 racing calendar has 20 races each season with each Formula 1 firm (called 'F1 team' or 'F1 Constructor') racing two drivers in almost identical cars. Each driver and their team is awarded points depending on the driver's finishing position. FIA, the governing body for Formula 1, requires all teams to construct their chassis internally (hence the name 'constructor championship' for the team championships). Teams can source engines and other components externally though a few teams chose to build their own chassis and engines (e.g. Ferrari, Mercedes, and Renault).

Formula 1 offers at least four distinct advantages as a contextual setting for this study.

- Formula 1 is composed of a global network of constructors, suppliers, and automotive manufacturers which are comparable in organisational size, technological knowhow, and are all focused on producing one specific product that is the race car. These teams are simultaneously collaborating to adopt to the technological challenges and regulatory direction involved in building a Formula 1 car and competing at the Grands Prix. This offers a remarkable 'natural control' and strengthens the validity of empirical analysis (Aversa et al., 2015; Castellucci and Ertug, 2010; Marino et al., 2015).

- Formula 1 teams' performance can be quantified, measured, and compared. This offers a rare opportunity where availability of performance metric, that is grand prix results, helps in understanding effects of movement of individuals within the network and how that movement affect the tacit knowledge transfer process.
- There is a wide availability of data on performance metric, movement of individuals, and technological capabilities of Formula 1 teams stretching from 1950s to the present day.
- Formula 1 as an industry operates at a fast clockspeed and is reliant on innovation for competitive advantage.

The top teams in Formula 1, such as Ferrari, Mercedes, McLaren, and Red Bull have yearly budgets, including sponsorship, partners, and Formula 1 prize money payments, more than $500 million (Hall, 2016). Lower ranked teams such as Force India, Williams, and Sauber have yearly budgets anywhere between $100 million to $200 million. Despite stringent regulatory measures and similar budgetary, technical, and human resources constraints, teams perform differently. This implies that the differences in team performance cannot be explained by vertical integration or corporate budget alone. This study explores how teams with similar resources derive competitive advantage.

### 1.3.The Contribution to the Research: Gatekeepers and Small World Networks

This research establishes that movement of key individuals (gatekeepers) facilitates tacit knowledge transfer. In this context, there is a correlation between movement of individuals and the performance of the organisation. Specifically, those individuals who perform higher on certain social network analysis metrics have a positive effect on the performance of the organisation. The research finding challenges the relation based and organisational ecology views of inter-organisational networks and argue that budgetary, structural factors, and organisational level cooperation cannot explain performance differentials, and it further shows that individuals, the gatekeepers, who are critical for knowledge transfer success and organisational performance.

Study accomplishes this by mapping movement of networked individuals and the accompanying tacit knowledge flows in the inter-organisational network of Formula 1. By identifying a framework to track movement of tacit knowledge transfer within inter-organisational networks, this study also allows for a closer examination of tacit knowledge transfer process and has implications for wider knowledge management practices in inter-organisational networks.

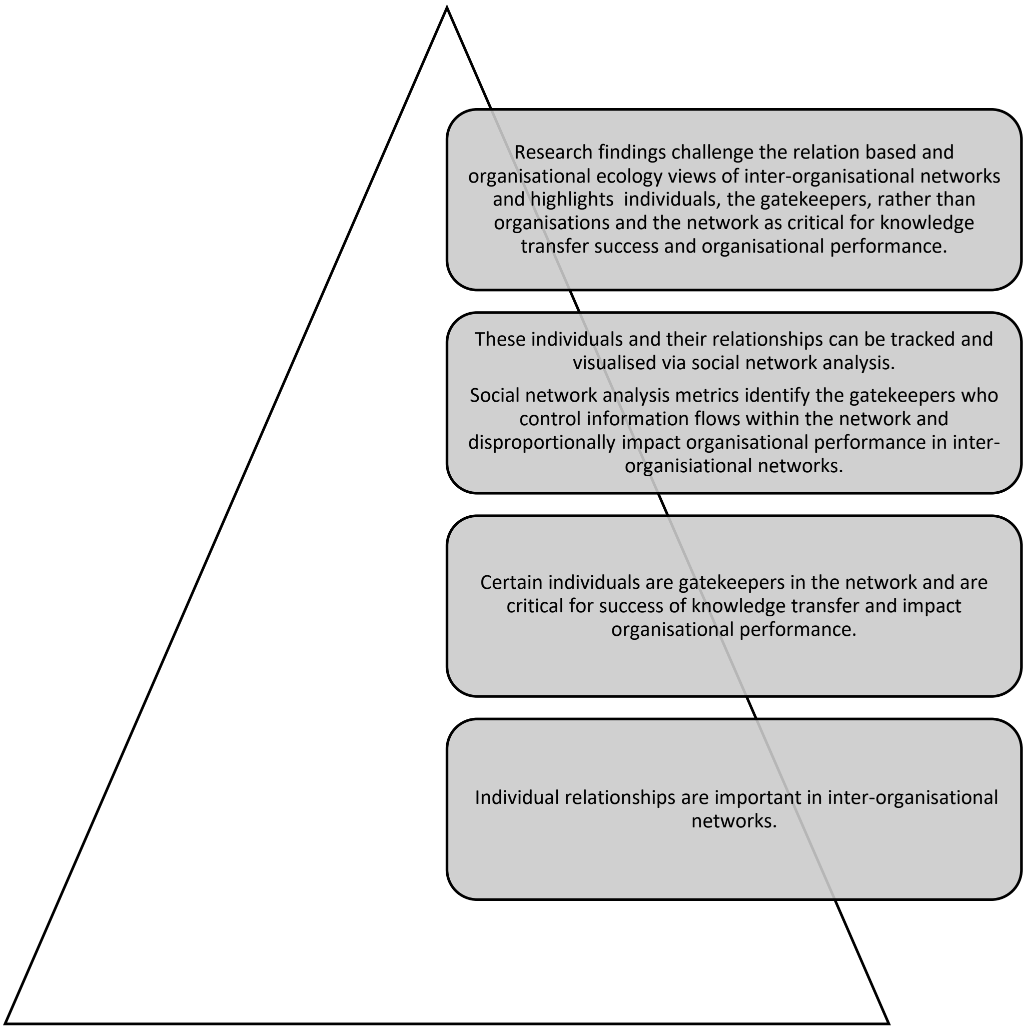



Figure 1 Research contribution

Research findings identify the non-traditional nature of Formula 1 as an industry and its ability to consistently innovate and adopt technologically in response to external factors such as regulatory changes and improvement in competitors' performances within a limited time frame. Formula 1 accomplishes this via movement of individuals, which introduces novel knowledge within the organisation, and play different managerial and technical roles. The process by which Formula 1 adopts and responds to these external factors offers lessons for other industries such as video game developers and semiconductor chip makers which share Formula 1's fast-clockspeed (Fine, 2010).

The inter-organisational network of Formula 1 is a small world structure which facilitates knowledge transfer and innovation. This is relevant for industries which share Formula 1's characteristics of technological complexity, evolution, and competitive-cooperative alliances such as aerospace, pharmaceutical, semiconductor chip makers, and video game developers. Research finds that regulation changes are key drivers of technological discontinuities in Formula 1, and this study shows how the movement of networked individuals plays an important role in teams' ability to respond to these regulation changes with innovation and technology improvement.

## 1.4. The Structure of the Thesis

Chapter 1. Introduction. This chapter has introduced the background to the research and the research questions that guided the investigation. This section presents an outline of the structure of the document.

Chapter 2. Literature Review: Knowledge Transfer and Social Networks. This chapter begins by a survey of literature on knowledge transfer, tacit knowledge transfer and role of individuals in that process in inter-organisational networks. The next sections discuss two primary research strategies for studying inter-organisational relationships, and identify social network analysis (and small world phenomena) as the suitable framework for this study. The chapter ends with discussion of research questions and choice of the context for this study.

Chapter 3. Research Philosophy and Methodology. This chapter begins with the section describing philosophical underpinning for methodologies and their triangulation. The next sections and subsections discuss interviews, case studies, and social network analysis.

Chapter 4. Context: Formula 1 – A Small World. This chapter begins with a brief technological overview of Formula 1 and description of key technological discontinuities. This chapter identifies and categorises interviewees' responses under labels used for analysis. The chapter ends with a section identifying key themes of the interview analysis.

Chapter 5. Interviews and Case Studies: Qualitative Analysis: This chapter identifies and categorises interviewees' responses under labels used for analysis. The chapter ends with a section identifying key themes of the interview analysis. The next sections discuss three cases, Renault RS01 (first Formula 1 car to use turbocharges), Ford DFV (the most successful grand prix engine in Formula 1 history), and the Ross Brawn's time at Ferrari and his competitors. The chapter ends with identifying key themes that have emerged from the analysis and compares them against interview findings.

Chapter 6. Social Network Analysis: Quantitative Analysis. This chapter begins with the network graph and metric table for Formula 1 network (1992 – 2010). This is followed by discussion of team performance and small world nature of Formula 1. Next sections identify the top and bottom performing nodes. This is followed by description of how top placed nodes have positive effect on team's performance and how nodes in certain roles affect team performance to a greater degree than others.

Chapter 7. Research Findings and Discussion. This chapter discusses the key research findings categorised under the themes of movement of individuals and tacit knowledge, nature of Formula 1, small world behaviour of the Formula 1 network, way of doing things, and regulations and geographical proximity.

Chapter 8. Conclusion. This chapter concludes by highlighting the key contributions to knowledge and limitations of this study.

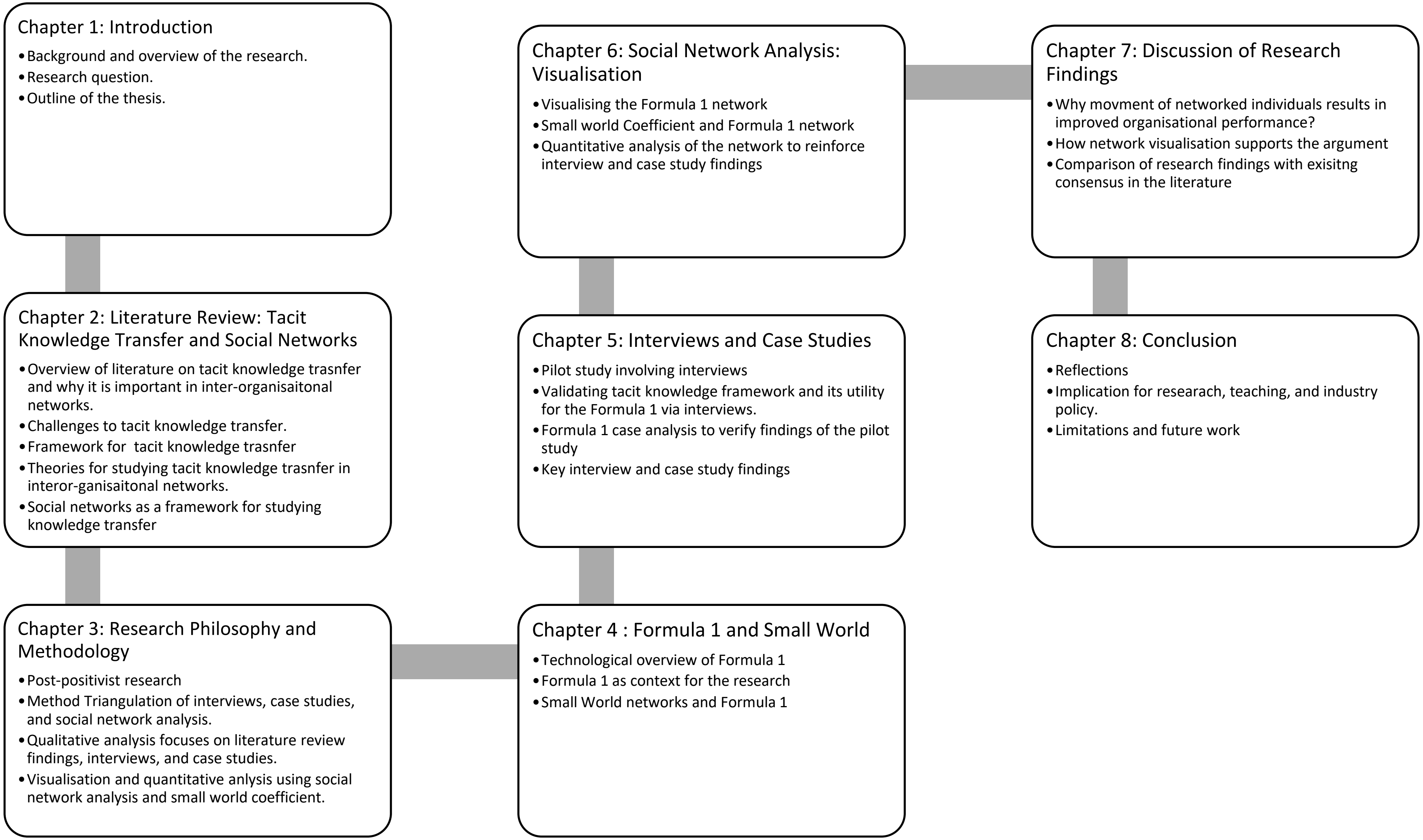



*Figure 2 Thesis outline*

# Chapter 2: Literature Review: Knowledge Transfer and Social Network Analysis

Knowledge transfer is essentially an innovation process (Robbins and Milliken, 1978, Fores, 2016, Iyer et al., 2017) and it has been made more difficult by rapid and radical technological changes and competitive pressure (Griffin, 1997). Knowledge transfer is incentivised by lower costs involved in replicating knowledge than the original costs of creation (Winter, 1995). Knowledge Transfer is also a process by which one firm is affected by the experience of another (Argote et al, 2003). In the context of organisations, knowledge transfer is defined as the process through which organisational nodes- teams, units, and organisations exchange, receive, and are influenced by the experience and knowledge of others (Argote, 2012)

Studies have considered other definitions of knowledge transfer, for instance Hansen (1999) and Tsai (2002) define knowledge transfer as knowledge sharing, Gupta and Govindarajan (2000) and Schulz et al. (2014) describe knowledge transfer as knowledge flow and Darr et al. (1995) and Lyles and Salk (1996) focus on knowledge acquisition. Literature also highlights the boundaries for the knowledge transfer Inkpen and Tsang (2005) and how inter-firm knowledge transfer is more challenging than intra-firm knowledge transfer.

Firms' are increasingly using alliances and mergers and acquisition to acquire external knowledge and it has become a central plank for firm's success (Bresman et al. 1999, Lane et al., 2001, Iyer et al., 2017). Intra-organisational knowledge transfer is another aspect of knowledge transfer playing a central role in a firm's success (Gupta and Govindarajan, 2000; Schulze, 2001, Szulanski et al., 2016). These two aspects, strategic alliances and knowledge transfer within and across a firm have become focus of strategy and organisation research.

Knowledge transfer can be unilateral or bilateral (reciprocal flow) and explicit or implicit. Implicit knowledge transfer involves innovations/improvements in one firm diffusing through an industry or region whereas in explicit knowledge transfer, members of strategic alliances initiate the process of knowledge transfer (Argote and Ingram, 2000). One of the primary mode for transfer of knowledge, either tacit or explicit between organisations is via movement of individuals (Deeds, 2003). This does not however prevent analysis of knowledge transfer at higher levels such as departments, organisations, and industry (Argote and Ingram, 2000).

There are three levels of analysis for the study of knowledge transfer (Gupta and Govindarajan, 2000), nodal (within a firm), dyadic (between two firms), and systematic (within an inter-organisational network). This study is looking at systematic level and how to analyse the process of knowledge transfer within an inter-organisational network.

Rebenitsch and Ferretti (1995) state that there are three important aspects to transfer of a technology, first is the technology itself. That is the nature of the technology that is being transferred. The second aspect is that of transfer mechanism, as in how and by what means the technology is transferred and the third aspect is concerned with the receiving firm, and its technological capabilities and ability to absorb knowledge. The last aspect is critical for knowledge transfer success. If a recipient is not able to decode and absorb the knowledge, then irrespective of the transfer mechanism and knowledge content, the process will not be successful.

The context in which the technology has been developed by source firm is paramount to the success of knowledge transfer as the recipient firm cannot absorb the knowledge or even understand what is being transferred if it is working in a different context (Schulze et al., 2014). This is important in the context of inter-organisational networks. For instance, in a large supply chain network, a supplier working in minerals and ore mining and the end user in the construction industry have different working contexts. Without contextualisation, knowledge transfer in such a scenario is difficult.

Szulanski (1996) explores this further and suggests four distinct stages of the knowledge transfer process,

- Initiation (firm looks for required knowledge or offered relevant knowledge)
- Implementation (focus of this dissertation)
- Ramp up (recipient begins to use the knowledge)
- Integration (recipient firm achieves satisfactory results with the transferred knowledge. Successful knowledge transfer results in knowledge getting embedded in the knowledge stock of the recipient firm and leads to a competitive advantage)

Each stage of this process is affected by variables involved (Szulanski, 1996), that can either facilitate the process or create barriers. Some of these variables are, trust (Chen, 2004;

Norman, 2002; Schulze et al., 2014), strength of ties (Cavusgil et al, 2003), tacitness of knowledge (Chen, 2004; Norman, 2002; Squire et al., 2009), absorptive capacity (Tsai, 2001; Lichtenthaler and Lichtenthaler, 2009), barriers to inter-firm and intra-industry knowledge transfer, tacit (Szulanski, 1996; Norman, 2002; Squire et al., 2009), overlap of resources/technologies (Song et al., 2003), prior alliances (Lyles, 1998; Lyles and Gundegran, 2006), and proximity to the core competencies (Quintas et al., 1997, Ahuja, 2000).

Out of these variable, certain key variables are frequently identified in literature as critical facilitating dimensions or presenting barriers to knowledge transfer (Szulanski, 1996; Chen, 2004, Norman, 2002; Lyles and Gundegran, 2006; Ahuja, 2000; Song et al., 2003, Tsai, 2001; Schulze et al., 2014);

Table 1 Dimensions of knowledge critical for knowledge transfer

| **Dimensions of knowledge** | |
|---|---|
| Tacitness | Knowledge about the transfer process in strategic alliances is tacit and difficult to transfer (Szulanski, 1996, Szulanski et al., 2016) |
| Absorptive capacity | Absorptive capacity is critical to success of strategic alliances (Tsai, 2001) |
| Prior alliances | Choice of partner for a strategic alliance is affected by the experience of prior alliances (Gulati, 1998) |
| Proximity to core competencies | Quintas et al. (1997) highlight the paradox of encouraging the free flow of knowledge while protecting the core competencies. |
| Trust | Schulze et al. (2014) highlights trust as critical for success of knowledge transfer |

Researchers have studied knowledge transfer in strategic alliances with a focus on the motivation for knowledge transfer. Firms collaborate and get into alliances to access knowledge already residing within the alliance partner(s) (Gulati, 1988) or create new knowledge and capabilities (Inkpen and Tsang, 2005, 2007). Collaboration has been considered an effective and efficient way to acquire knowledge and facilitate innovation. (Adams et al., 2006). Grant and Baden-Fuller (2004) argue that alliances contribute to efficiency in the application of knowledge by, first, improving efficiency with which knowledge is integrated into the production of complex goods and services, and second, increasing efficiency with which knowledge is utilized.

Studies have also focused on the relationship between knowledge transfer in alliances and innovation; firms that create and use knowledge rapidly and effectively are able to innovate faster and successfully (Tamer Cavusgil et al., 2003). In strategic alliances, knowledge is located 'between' the organisations and not 'within' them (Hardy et al., 2003; Quintas et al., 1997) highlight the boundary paradox where firms have to find a balance between encouraging the free flow of knowledge and protecting their core competencies so as to stay competitive in the industry whilst dealing with knowledge transfer in alliances.

Knowledge transfer has also been studied in specific industries; Lam (1997) studied a joint venture in a high technology industry and highlighted the importance of 'degree of tacitness' of knowledge. Studies have also focused on how knowledge is actually transferred between partners (Appleyard, 1996; Baughn et al., 1997; Choi and Lee 1997; Dodgson 1996; Mowery et al., 1996). Garud and Nayyar (1994) examined dimensions of technological knowledge that affect knowledge transfer over time and highlighted the role of 'transformative capacity.' Simonin (1999) studied the role of knowledge ambiguity pertaining to the process of knowledge transfer in strategic alliances and found that knowledge ambiguity acts as a mediator of tacitness, prior experiences, complexity, cultural distance, and organisational distance on knowledge transfer. Lyles and Salk (1996) study shows how knowledge is acquired in alliances and joint ventures from parent organisations.

Doz (1996) examined implications of knowledge and learning on the evolution process of the collaboration and its outcomes. Cummings and Teng (2003), in their study found that 'more types and numbers of transfer activities contribute to the transfer success". Their paper also suggested that in new product development, reducing the norm distance; the extent to which involved parties share similar understanding and ideas about the knowledge transfer project between the source and recipient is essential to transfer success. Norman (2002) found in her research that in a strategic alliance, firms are more protective when capabilities they contribute to the alliance are highly tacit and core and recipient firm has higher learning intent.

Schulze et al. (2014) discuss the impact of disseminative capability on knowledge transfer in alliances and collaborations in automotive industry and identified variables affecting knowledge transfer success. Pinch et al. (2003) studied how clusters evolve over time and affect the learning capacity of firms and facilitating rapid dissemination of knowledge. Inkpen (2008) studied knowledge transfer in an alliance between Toyota and General Motors with focus on organisational processes used to transfer knowledge. Jenkins and Tallman (2015) highlight the role of geography of knowledge source in internalizing the knowledge from another firm, and eventually radically transforming the recipient firm.

Researchers have studied the motivation behind knowledge transfer in strategic alliances (Kogut, 1988; Inkpen and Tsang, 2005; Grant and Baden-Fuller, 2004), how 'knowledge is actually transferred' (Appleyard 1996; Aversa et al., 2015; Baughn et al., 1997; Choi and Lee 1997; Dodgson 1996; Mowery et al., 1996), and variables affecting knowledge transfer (and success) (Garud and Nayyar, 1994; Simonnin, 1999; Cummings and Teng, 2003; Schulze et al., 2014). In literature, while some studies, such as Lam (1997), Cummings and Teng (2003), Pinch et al. (2003), Lin (2007), and Jenkins (2010) do focus on specific variables (or characteristics) of an industry when discussing the knowledge transfer process, but there is a dearth of research on the mechanisms for transfer of knowledge.

Recent studies in the literature have also highlighted the critical role of variables, technological competence (Ahuja, 2000; Pinch et al., 2003; Aversa et al., 2015), competition (Yoshino and Rangan, 1995; Gomes-Casseres, 2006; Pinch et al., 2003), and evolution of knowledge (Rond and Marjanovic, 2006; Jenkins and Tallman, 2015) in the implementation of knowledge transfer process in strategic alliances. These industry variables (competence, competition, and evolution) and knowledge transfer dimensions are constantly interacting within the inter-organisational network which is also a source of organisational competitive advantage (Dyer and Singh, 1998; Van Wijk et al., 2008) and facilitates knowledge transfer (Easterby-Smit et al., 2008).

### 2.1. Tacit Knowledge Transfer

Codifying knowledge (Chen, 2004), research and development collaborations (Cummings and Teng, 2003) and inter-personal networks (Reagans and McEvily, 2003) greatly reduce the knowledge transfer time in strategic alliances. Primary variables affecting knowledge transfer are, discussion bias (Kim, 1997), firms focusing on the collectively held knowledge, and failing to recognize the unique individual knowledge. Trust, communication and supplier flexibility also influence knowledge transfer (Zhao and Lavin, 2012).

Argote and Ingram (2000) argue that problem of knowledge transfer in organisations go beyond the individual level and instead involves higher levels such as units within the organisation, department or organisation itself. Most of the human knowledge is context bound and highly embedded within the individuals in the organisation, and this is further exaggerated if the organisation is working in a technologically advanced field, such as automotive industries or IT industries (Lam, 97). Furthermore, Nelson and Winter (1994) argue that knowledge is mostly tacit, context bound and firm specific and therefore presents a considerable challenge when it comes to transferring one firm's knowledge to another.

To further understand the knowledge transfer, one must consider the nature of knowledge and how it resides in humans. Michael Polanyi (1964, 1967; 4) said,

"*I shall reconsider human knowledge by starting from the fact that we can know more than we can tell"*

Polanyi is referring to 'tacit' knowledge with 'know more than we can tell' clause. He argues that while 'explicit' knowledge can be articulated, codified and written down/stored in a media, and hence making it relatively easy to transfer it, tacit knowledge can neither be easily articulated nor codified, even by an expert practitioner. Manuals are a good example of explicit knowledge whereas knowledge of how to design and integrate various mechanical and electrical components to build a grand prix race car is an example of tacit knowledge.

In this context of 'tacitness', knowledge transfer presents a challenge. Organisations, deposit Rebenitsch and Ferretti (1995), are a mash of embodied knowledge that includes technological expertise, interpersonal relationships, and organisational hierarchy. Their conclusion suggests that knowledge 'construct' or 'architecture' of each firm is unique and a serious hindrance to knowledge transfer. Therefore, the ability of a firm to clearly articulate the embedded knowledge becomes crucial for successful knowledge transfer.

Lam (1997: 994) further elaborates on this in his study of a joint venture between a British and Japanese firm, and highlights the importance of 'degree of embedded knowledge and social organisation systems' of firms to success (or failure) of knowledge transfer. He further argues that in the context of 'high-technology' collaborations, '…*difficulties in the transfer of knowledge arise not simply from the 'tacit' nature of knowledge itself, but from differences in the degree of tacitness of knowledge and the way in which it is formed, structured and utilized* *between firms in different countries.*' This is relevant to the context of this research as Formula 1 teams collaborate with, and in some instances are part of the wider automotive industry.

Tacit knowledge is most difficult component of knowledge transfer process. Polanyi (1964) has argued that *tacit knowledge is not articulated and unspoked.* Tacit knowledge has an *intuitive and personal* character and therefore is much more difficult to give structure and communicate. Nonaka and Takeuchi (1991) argue that tacit knowledge resides within individuals' minds and their abilities. Transfer of tacit knowledge is dependent on transmission capacity (Argote et al., 2003) and learning of individuals (Ferdows, 2006). Tacit knowledge has many elements that facilitate business routines and are transferable between individual or groups of individuals. It represents the characteristic, corporate structure, and accumulated knowledge base of an organisation (Battistella et al., 2016). Tacit knowledge can be accumulated through a process of continuous and dynamic development of the knowledge already within the organisation. This development and evolution of the knowledge already residing within the organisations take place through the process of accumulation of new experience, working practices, and operations involving direct contact.

Argote and Ingram (2000) highlight the difficult of replicating tacit knowledge and its potential benefit to the competitive advantage of the firm. This implies that organisations have to continuously regenerate and adapt their skillset and promote knowledge at every level of the firm. This approach to tacit knowledge is akin to the resource based view of the firm (Wernerfelt, 1984; Barney, 2001a, 2001b; Lado and Wilson, 1994; Penrose, 1959) where firms' derive their competitive advantage from a *bundle of resources* such as assets, capabilities, attributes, (tacit and explicit) knowledge, and internal practices. Tacit knowledge is important for a firm's success in dynamic and inter-connected environments (Lavie and Drori, 2012; Gulati et al., 2011; Sirmon et al., 2007).

### *Framework for Tacit Knowledge Transfer*

The literature survey has highlighted a series of different attributes that affect the knowledge transfer process. These attributes can be arranged into a framework to focus the study on the process of knowledge transfer in inter-organisational networks.

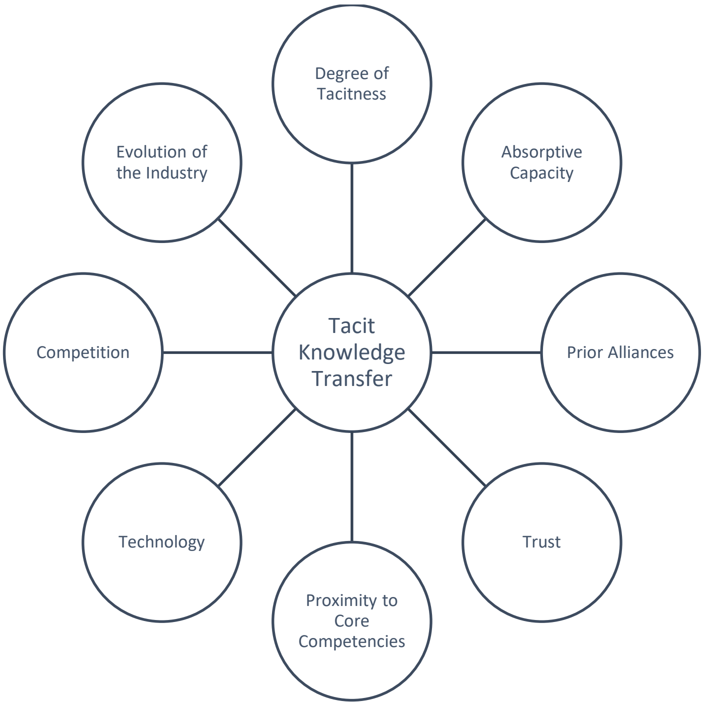



Figure 3 Framework for Tacit Knowledge Transfer

The tacit knowledge transfer takes place via individuals moving and interacting within and without the organisational boundary in the inter-organisational network. This process is affected by many factors, as shown in figure 3. The factors described in figure 3 not only affect the tacit knowledge transfer but also interact among themselves. The following table gives a summary of how these factors interact and affect tacit knowledge transfer,

Table 2 Factors affecting tacit knowledge transfer

| | |
|---|---|
| Degree of tacitness<br>*A history of prior alliances and absorptive capacity can facilitate transfer of highly context bound knowledge* | Highly context bound, and tacit knowledge is difficult to transfer. |
| Absorptive capacity | Ability to identify and assimilate relevant knowledge in partners is a key factor for the success of knowledge transfer. |
| Prior alliances<br>*Trust between network partners grows with a history of successful prior alliances.* | A history of prior alliances can encourage knowledge transfer between partners. |
| Trust | High level of trust encourages knowledge flows and exchanges related to core competencies. |

| | |
|---|---|
| Proximity to core competencies<br>*Trust between organisations can facilitate a more cooperative relationship around core competencies.* | Organisations are reluctant to share their core competencies with their partners. |
| Technology | Specialised and complex technologies are difficult to transfer. |
| Competition<br>*Competition beyond alliance boundaries motivates knowledge transfer.* | Competition between alliance partners can be detrimental for knowledge transfer process |
| Evolution of the industry | Industries with fast clockspeeds affect knowledge transfer behaviour of organisations within the industry network. |

Tacit knowledge transfer has implications for organisational performance and since, tacit knowledge resides within individuals, the linkages and relationships among them also have an impact on organisational performances.

This discussion has highlighted the role played by individuals and their relationships in tacit knowledge transfer in inter-organisational networks. The next section discusses inter-organisational relationships and methodologies used to study them.

## 2.2. Inter-organisational Relationships

Understanding inter-organisational relationships is fundamental to understanding knowledge transfer process in networks of organisations. Inter-organisational relationships have received growing attention from management scholars. This is in part driven by realisation that organisations do not fail or succeed in isolation but as part of an industry network.

Scholars in strategy research and system thinking identify goals (such as sustainability and ability to respond to changes) that can only be achieved if organisations operate within a network and manage their social interactions (Fiksel, 2006). Helfat et al. (2009) identify inter-organisational networking as one of the key strategies for maintaining flexibility and ability to respond quickly to challenges. Different theories have been proposed by different scholars to study inter-organisational relationships such as transaction cost economics (Ebers and Oerlemans, 2016), or resource based view as part of agency theory (Arya and Lin, 2007), and network theories and social network analysis (Bergenholtz and Waldstrom, 2011). The two main perspectives for studying inter-organisational relationships are distinguished by how they explain inter-organisational relationships (Rossignoli and Ricciardi, 2015).

The first perspective consists of theories which explain inter-organisational relationships in terms of coordination and control needs. These theories describe inter-organisational relationships as founded on *opportunities and bounded rationality* (Rossignoli and Ricciardi, 2015). Transaction cost economics (Williamson, 1975, 1981, 1989), agency theory (Eisenhardt, 1989), and resource dependency theory (Pfeffer and Salancik, 2003) are the main theoretical perspectives following this approach. Scholars subscribing to these theories maintain that organisations in inter-organisational networks are trying to control the network's critical aspects to pursue their own goals.

Theories following the second perspective explain inter-organisational relationships in terms of strategic challenges and posit that these relationships determine an organisation's strategic capabilities of competitiveness and innovations. Organisational ecology (Hannan and Freeman, 1977), resource based view (Dierickx and Cool, 1989; Barney and Arikan 2001; Peteraf 1993; Lado and Wilson 1994; Dyer and Singh, 1998), and social network analysis (Hansen, 1999; Burt, 2001, Burt, 2005; Uzzi and Spiro, 2005; Ahuja, 2000; Schilling and Phelps, 2007; Phelps et al., 2012) follow the second approach.

Table 3 inter-organisational relationship theories (adopted from Rossignoli and Riccardi, 2015)

| Perspective | Theories |
|---|---|
| Coordination and Control Needs | Transaction Cost Economics,<br>Agency Theory,<br>Resource Dependency Theory. |
| Strategic Challenges | Organisational Ecology,<br>Resource Based View (and Relational View),<br>Network Theories and Social Network Analysis. |

### *2.3.1. Coordination and Control Needs*

#### Transaction Cost Economics

Transaction Cost Economics theory has its roots in work of Commons (1934) and Coase (1937). Coase (1937) argues that if production is assumed to be regulated by price movements alone, then no need arises for an organisation.

Coase's work attempted to justify the existence of organisations and how they organise internally. This work was later expanded by Williamson (1981) who co-opted the microeconomic approach, taking a contradictory position to the traditional view of the firm as defined in neo-classical theory. The central thesis of transaction cost economics is about the role of price as the co-ordinating mechanism and the associated transaction costs. Thus, more complex the transactions, higher the costs involved.

Rossignoli and Ricciardi (2015) identify the dynamic between hierarchy and market as central to transaction cost theory. This approach put an emphasis on the transaction as the base analysis unit. Williamson (1989) argues for the need of organisations by highlighting how certain combination of factors can make markets inefficient mechanism for governing transactions, and hence making a hierarchy cheaper to use.  Transaction cost economics aims to explain unforeseeable costs arising from unpredictable markets such as bounded rationality, information asymmetries, and the potential for opportunistic behaviour.

### Agency Theory

Work of scholars such Wilson (1968), Arrow (1986), Ross (1973), and Jensen and Meckling (1976) led the foundation of agency theory. Agency theory is concerned with sharing of risk. Agency problem occurs when one party or individual; called the principal, delegates work to another party or individual; called the agent who performs the work. The agency relationship framework is universal and can be applied in any context. For instance, the relationship between a project leader and researcher can be analysed with this framework. It can also be used to analyse and study inter-organisational relationships, such as supply chain relationships which are affected by agency problems.

Jensen and Meckling (1976) used the lexicon of 'contract' to describe the relationship between the agent and the principal. Contract is the primary unit of analysis in agency theory. Agency theory aims to determine the most effective contract and other aspect of the agent and the principal such as their self-interest, rationality, attitude towards risk. Aspects such as organisations and their conflicts and the information as commodity are also explored through agency theory.

The agency theory and transaction costs economics arise from two different traditions in economics. The former focuses on contracts between two entities or individuals, regardless of boundaries whereas later is focused on organisational boundaries.  But agency theory and transaction costs economics also share many similarities as observed by Williamson (1975). Assumptions of self-interest and (bounded) rationality are foundational for both theories and focus is on economic mechanisms for managing conflicts, incentives, and prices. However, both perspectives do not take social and political aspects into consideration. Socio-political mechanisms of power, negotiations, and personal relationships are not considered.

### Resource Dependence Theory

Scarcity of resources is one of the primary reason for uncertainty in the competitive market. Efforts of competitors control critical resources beyond their organisational boundaries and unpredictable and sudden changes in market conditions are other contributing factors. This motivates firms to form alliances and relationships, especially with the firms with complementary competencies and resources.

Pfeffer and Salancik (2003) build their theory of resource dependence around this central theme. In resource dependence theory, operating environment and social context of the organisation plays an important role. Even the decisions made within the organisational boundary is affected by the external environment.

Organisations are interdependent and part of a wider network of social relations. Driving force behind this interdependence, which could be reciprocal or partial, is lack of any firm's ability to generate all the resources it needs to operation and be competitive with the external environment. Resources are dependent on the external environment and its inherent complexity and dynamism (Pfeffer and Salancik, 2003.)

### *2.3.2. Strategic Challenges*

The inter-organisational relationships theories that focus on coordination and control needs do not consider the social and political context in which organisations operate and the role of individuals within that context. In this regard, theories which treat inter-organisational relationships as part of strategic challenges faced by organisations are more comprehensive.

## Organisational Ecology

The framework of organisational ecology analyses inter-organisational relationships through the lens of evolutionary biology. Organisational ecology first came to the attention of scholars in the 1970s (Hannan and Freeman, 1977). Different organisational theories share one core idea that is the organisational type, also known as organisational form. Organisation type is an identifier for the class of an organisation. This type is reflection of organisations that share relatively same set of external environmental vulnerabilities. Organisations of similar type share same set of rules to produce their outputs and compete for same resources.

Organisational type is analogous to what is labelled the business model in present day discussions between management scholars. Hannan (2005) identifies two primary factors that influence organisations, competition and constraints. Competition influences organisations by making resources scarce. These resources can be financial, supplier relationships, or the end consumer. Irrespective of an organisation's relationship with its competitors, it is influenced by the competition for resources. Constraints can be internal and external, and come in form economic constraint, consumer opinion and choices, or technological innovation. Organisational ecology view is a firm level tool to explore inter-organisational relationships and does not explore the relationship dynamics at individual level.

## Resource Based and Relational View of the Firm

Wernerfelt (1984) in his article, *A Resource based View of the Firm* argued that a firm's resources can be a source of competitive advantage. For these resources (and capabilities) to provide competitive advantage and financial success, they must be durable, heterogeneous, immobile, and inimitable (Barney and Arikan, 2001; Lado and Wilson, 1994). This leads to the question of how some firms can sustain competitive advantage and financial profit, whereas others fail. Wernerfelt (1984) argued that firms are more than just a bundle of contracts, they are *bundle of resources* (Penrose, 1959). Resources mean assets, capabilities, attributes, (tacit and explicit) knowledge, and internal practices.

A firm controls its resources to drive efficiency, efficacy, and *super performance* (Barney and Arikan, 2001). Superior performance is a concept that refers to higher than expected value generated by resources, resulting in implementation of (value creation) strategies that are difficult for competitors to copy. This approach to strategic analysis highlights a firm's ability to generate more value than its competitors as a source of competitive advantage (Barney and Arikan, 2001) This ability is dependent on physical assets such as hardware, technologies, production facilities, geographical location, supply chain, and non-physical assets such as intellectual capital and tacit knowledge residing within individuals in the organisation.

A resource based view is the dominant paradigm in the field of operations management and sub fields (supply chain management, operations strategy, performance management, and product and service innovation) and strategy management research (Hitt et al., 2016). Many recent developments in the resource based view come from scholars working in the strategic management research (see Dyer and Singh, 1998). The field of strategic management is concerned with understanding how firms differentiate themselves from their competition to achieve a sustained competitive advantage and therefore it is not entirely surprising that researchers working in the field translate Penrose (1959) and Wernerfelt's (1984) ideas for understanding how firms gain competitive advantage.

Within the subfields of operations management, the resource based view is particularly relevant for operations strategy. Operations strategy deals with how to effectively use inputs and process capabilities to produce outputs that help to achieve business and corporate goals (Hitt et al., 2016; 79). These goals include ability to innovate, product related competencies, quality, and profits (Ahmed et al., 1996). Anderson et al. (1989; 133) argue that "*proper strategic positioning or aligning of operations capabilities can significantly impact competitive strength and business performance of an organization.*" Since operation strategy treats operations as a strategic process of positioning resources and capabilities, the resource based view complements operations strategy with a focus on acquiring and bundling the strategic resources to create capabilities that are leveraged to achieve a competitive advantage (Tiff et al., 2015; 80). The resource based view also emphasises synchronisation of the processes involved in acquiring, bundling, and leveraging resources, which is a focus for operations strategy research (Shah and Ward, 2003; Pilkington and Meredith, 2009).

This study is located at the intersection of operations strategy and strategic management research, therefore the resource based view, and other corollaries need to be explored as theoretical framework for the purposes of this research.

Over the years, scholars have built on the resource based view, and its treatment of resource and assets to develop '*relational view*' (Dyer and Singh, 1998). The relational view is concerned with the critical resources of a firm and its ability to extend beyond organisational boundaries. Dyer and Sing (1998) identified the theoretical foundation for sources of inter organisational competitive advantage, and the inter-organisational relationships as an important unit of analysis. Gulati and Westphal (1999) also explored the concept of the network of inter-organisational relationships as a source of competitive advantage. Lavie and Drori (2012) built up on the concept of the relational view and network as a source of competitive advantage to argue that an organisation in a network can derive value from *resource that are not fully owned or controlled by itself*. Stronger inter-organisational links lead to resources with idiosyncrasies, making them difficult to imitate. This leads to a sustained competitive advantage for the firm.

The relational view builds on the foundation of the resource based view and highlight the critical role played by inter-organisational relationships ('resource network') in providing a sustainable source of competitive advantage.

Some scholars also focus on dynamic capabilities of firms and the importance of agility in an inter-organisational network (Eisenhardt and Martin, 2000; Helfat et al., 2009; Shuen and Sieber, 2009). Unlike the resource based view, this approach is more concerned with competitive survival than competitive advantage. The main thrust of the dynamic capabilities approach is that firms can only survive if they are agile and adaptive, have dynamic capabilities, and innovate on their resource base. This aspect of agility is also treated by network theories in terms of the individual and organisation's position in the network.

Despite its dominance in strategy and operations strategy research, resource based view theory has been criticised for ambiguity regarding the dependent variable, inimitable resources, and its "*tautological*" treatment of valuable resources (Bromiley and Rau, 2016).

Kraaijenbrink et al.'s (2010; 350) review of resource based literature argues that the resource based view aspires to explain the internal sources of a firm's sustained competitive advantage; a view that reflects seminal papers in the field, such as Barney (1991) and Peteraf (1993). But an overview of literature demonstrates that few, if any, resource based view papers try to explain sustained competitive advantage. Newbert's (2007) review of 55 empirical articles on resource based view found that only 2% of the studies used *sustained competitive advantage* as the dependent variable and it was actually *performance* that was the dependent variable in 93% of the studies. Another review (Armstrong and Shimizu, 2007) of 145 empirical resource based view articles found only 4 articles that "*even tried"* to measure sustained competitive advantage. Similarly, in Crook et al.'s (2008) analysis, resource based articles put emphasis on performance differences and not on sustained competitive advantage. Bromiley and Rau (2016) argues that most resource based view studies do not specify what sustained means in sustained competitive advantage.

The second major criticism of resource based view is centred on resources and question of their imitability. Resource based view studies have argued that sustained competitive advantage comes from resources that are difficult to imitate and the organisations that do seek to imitate these resources are faced with *some level* of causal ambiguity (Barney, 1991, 2001a, 2001b; Peteraf, 1993; Lipmann and Rumelt, 1982; Hitt et al., 2016). This leads to the logical conclusion that organisations that do have these *inimitable resource* with some level of *causal ambiguity* do not understand themselves how these resources work. This also means that all physical resources such as capital, infrastructure, and supply chains are not sources of competitive advantage. This theoretical outlook essentially implies that a firm could not start doing business with what is known and develop resources that will provide sustained competitive advantage.

Resources based view studies also argue that resource must not only be inimitable but also *valuable* (Barney, 1991). Priem and Butler (2001) have criticised this view as *tautological* since the determination valuable resource within resource based view lies on firm performance. In response to these criticisms, resource based view studies have argued that a resource is valuable if it is rare, inimitable, and unsubstitutable (Barney, 2001a, 2001b). This valuable resource must also be *nontradeable* and *immobile* (Peteraf, 1993). This leads to a definitional problem. How does one determine if a resource is valuable when it is nontradeable and market cannot put a value to it? This discussion demonstrates that the resource based view is lacking when it comes to explaining sources of competitive advantage in inter-organisational networks.

### 2.3. Network Theories

While resource based and relational based views of firms do provide an inter-organisational perspective to analyse sources of competitive advantage and organisational performance, they do not take relationships among individuals within the inter-organisational network into account, and the level of analysis remains inter-organisational. This is where social network analysis has advantage over other perspectives for studying inter-organisational relationships. Social network analysis has its roots in sociology. Over the years, social network analysis has evolved into an interdisciplinary methodology with the incorporation of mathematics and statistics. It can be best understood as a tool to map and analyse the social structure of agents (or nodes) and their relationships (Freeman, 2004; Huber 2009; Moody, 2001; Wassermann and Faust, 1994). Recent years have seen a rise in number of social network studies (Monge and Contractor, 2003; Barabasi, 2003; Christakis and Fowler, 2009). Development of powerful computations tools for social network analysis (Agarwal et al., 2008; Lazer et al., 2009) have aided the application of social network analysis in different contexts to analyse and visualise networks.

Social networks are knowledge networks consisting of nodes (organisations or people). These nodes act as knowledge resource and database which can be accessed by other nodes. Nodes are linked with each other by social relationships. These relationships provide nodes a medium to search for information and knowledge, and a mechanism to diffuse information and knowledge through the network (Phelps et al., 2012)

In a social network, nodes are depicted as point and edges (ties or links) as lines. These networks can be analysed and coded using graph theory and social network analysis. Social network analysis facilitates a multi-level analysis (individual, intra and inter organisational, and network level) of knowledge transfer. Burt (2004) has studied the influence of social networks on individual creativity.

Hansen (1999) focused on intra firm knowledge sharing within a multinational electronics and computer company with more than $5 billion in annual sales. Hansen found that the effect on project completion times of weak (or strong) ties within the intra-firm network was contingent upon the complexity of knowledge which was to be transferred.

Phelps' (2010) studied alliance structure of 77 telecommunications equipment manufacturers and found that diversity of a firm' alliance partners increases its *exploratory innovation.* Exploratory innovation is innovation embedding knowledge that is novel to firm's existing knowledge base. Phelps also highlight that in a network where firm's alliance partners are also partners and have access to diverse information, has more exploratory innovation.

These social networks and knowledge transfer studies usually attempt to answer research questions concerned with networks' ability to facilitate (maximum) knowledge transfer, creations, and adoption. The two primary frameworks used by network scholars are, *the ego network,* and *the whole network.* Ego networks are focused on understanding role of one central node, called *ego* and how other nodes interact with ego. *Whole network* focuses on network wide behaviour and boundary conditions are defined as per the researcher's requirement (Phelps et al., 2012)

Studies in literature suggest that knowledge transfer can benefit from '*embeddedness into networks and spatial proximity to network partners'* (Fritsch and Slavtchev, 2007; Fritsch and Kauffeld-Monz, 2010). Research has highlighted how network with *closely related interests* can increase chances of successful and relevant knowledge transfer (Cowan et al., 2000; Cowan et al., 2007). Networks with embedded relationships encourage rapid and explicit feedback which in turn, facilitates generation of new ideas and solutions (Uzzi, 1998; Fritsch and Slavtchev, 2010). Frequency of interactions in such relationships have been shown to encourage trust, and consequently, increase in the quality of interaction (Daskalakis and Kauffeld-Monz, 2007).

Networks are constructed upon relationships between organisations and individuals and thus the knowledge transfer process in such networks is dependent on quality of these relationships and the nature of knowledge being transferred. The nature of knowledge, more so than spatial distance, determines the process of transfer. Therefore, if knowledge is tacit, and not explicit or codified, it requires personal interaction and contact between individuals (Polanyi, 1967; Asheim and Isaken, 2002).

Granovetter (2005) argues that a network (or a cluster within a network) with *strong ties* is a dense network of mutually connected nodes. The high frequency of interaction in such a network or cluster results in a considerable share of information flow being redundant, and any new information or knowledge is introduced in such a network or cluster through relationships which are outside the denser cluster (*weak ties)*.

Leyden et al. (2014) have drawn parallels between Granovetter's concept of weak ties (2005) and entrepreneurship. The identify search for knowledge as the primary characteristic of an entrepreneur and access to social network as key to acquisition of that knowledge. The *heterogeneous* social ties that form the social network facilitate innovation within the network (Burt, 2005; Leyden et al., 2014).

Researchers (Hoegl and Schulze, 2005; Burt, 2005; Mishra et al. 2017) highlight the role of brokers or gatekeepers in context of networks. These brokers or gatekeepers link different clusters within the network and provide a channel for flow of non-redundant knowledge. This provides for *additive* rather than *overlapping* access to knowledge and information (Burt, 2001). Studies have shown that *strong ties* within a cluster (Granovetter, 2005) and gatekeeper phenomenon (Mishra et al., 2017) are not mutually exclusive and can and do form a productive partnership.

### 2.4. Studying Inter-Organisational Relationships as Social Networks

Bergenholtz and Waldstrom (2011) argue for distinguishing between two types of networks in the context of inter-organisational relationships, a) networks of social interactions across organisational boundaries, and b) descriptive networks dealing with *existing social order between organisations.* Borgatti et al. (2009) highlight role of organisation's position within a network structure in influencing opportunities and constraints. In this context, scholars have argued that (Burt, 1992; Wasserman and Faust, 1994; Wellman and Berkowitz, 1988) that social network analysis offers a methodological tool for analysis of networks at different structural levels (that is individual, dyadic, triadic, and network level) and studying social contexts.

Scholars (Coviello, 2005; Hoang and Antoncic, 2003; Zaheer and Usai, 2004; Tsai, 2002) have argued that such an analysis of *inter-organisational* social network is considerably more complex than *intra-organisational* social networks, especially in context of inter-organisational entrepreneurial networks. Inter-organisational networks are inherently *unbounded* as observed by scholars in studies on apparel industry (Uzzi, 1997), American biotech industry (Higgins and Gulati, 2003), and global biotech industry (Gay and Dousset, 2005). Lack of natural (and nominal) boundaries in inter-organisational context presents a significant challenge to analysis. Laumann et al. (1983) identify two approaches to identifying meaningful boundary conditions in such scenarios, a realist approach where individuals (or nodes) themselves define the social boundaries and nominal approach where boundaries are imposed, conceptually, for the analysis. This study examines the Formula 1 industry as a bounded network and boundary specifications of nodes recognise only those nodes that are situated within the *Grand Prix Constructors-Manufacturers-Suppliers* network in Europe with 100 or more employees.

Complementing social network studies with institutional aspect of the network such as multi-level relationships and empirical setting produces a more comprehensive picture of network activities ((Dyer and Hatch, 2006; Owen-Smith and Powell, 2004; Paier and Scherngell, 2011; Sorenson and Stuart, 2008).

The last few decades have seen development of social network analysis as a powerful methodological tool with innovative metrics and visualization techniques (Borgatti and Everett, 2000; Freeman et al., 1991). These new developments have greatly expanded the applicability of social network analysis beyond relational studies. Innovative tools within the domain of social network analysis, such as exponential random graph models, longitudinal and dynamic network modelling, visualization, and directional analysis (Robins et al., 2007; Snijders, 2005; Moody et al., 2005; Bonacich and Lloyd, 2001) have led to new set of tests, such as assessing if betweenness centrality is linked to innovation (Gilsing et al., 2008), structural holes, core-periphery structures (Lazega et al., 2008), and structural network change over time (Ahuja, 2000).

## 2.5. Social Networks and Knowledge Transfer

Social network studies of knowledge transfer often focus on identifying a network structure that maximises knowledge transfer, creation, and adoption. Researchers use two types of framework for analysis network structures, the ego network and the whole network. Former is concerned with relationships of a single central nodes, called *ego* and studies of such networks explore the interactions of ego with other nodes and the relationship among them. Burt (2001) describes the concept of *structural holes* as a key tool to understand ego networks. A structural hole is said to exist between two nodes that are connected to the *ego* but do not share a tie between themselves, putting ego is a favourable position vis-à-vis the two nodes. This favourable position is due to the ability of *ego* to act as an information bridge between these nodes.

The second type of network framework is used to analyse the links existing throughout the node population. The whole network approach allows a research to set network boundaries depending on his/her needs. Phelps et al. (2012) identify knowledge creation, knowledge transfer, and knowledge adoption as typical dependent variables in whole network studies. In such studies, researchers aim to provide explanation of how network constructs or metrics influence the dependent variables.

These metrics define an array of network features, such as structural and relational. For instance, structural network metrics such as density or diameter are independent of the relationships and nature of knowledge (either created or flowing through) in the network. Metrics that explore influence of position of a node in the network on its knowledge outcomes are called centrality metrics. Centrality metrics define, either direct or indirect, contacts that a node has.

McEvily and Zaheer (1999) studied structural holes in ego networks and found that these holes enhance knowledge sharing and knowledge creation. Schilling and Phelps (2007) argue that it is the absence of structural holes or network closures that improve ego's performance. Other studies have highlighted how these contradictions can be explained, for example the nature of link between two nodes can be responsible for how network behaves with holes and closures (Ahuja, 2000). It can be argued that presence of diversity and in-depth knowledge within nodes in a dense network encourages knowledge sharing and its positive impact.

The clustering coefficient is a metric that measures tendency of nodes to cluster together. These clusters have a high density of links. Uzzi and Spiro (2005) argue that clustering is a positive for knowledge flows as it promotes social cohesion and facilitates knowledge sharing but an excessive clustering can result in *too much* cohesion, leading to a reduction in availability of novel knowledge within the cluster. Clusters that have nodes that are linked with other clusters are often most conducive for knowledge flows as they reduce network's average path length, and facilitate access to novel knowledge in other clusters.

There are other factors that affect knowledge management performance of inter-organisational networks. Behaviour of links between nodes, characteristics of nodes, the flow of knowledge through network links, and absorptive capacity are few such factors. Links between nodes are classified as strong ties if the relationships has existed for a long duration, collaborations have been frequent and repeated. These types of links encourage trust and reciprocity (Ruef, 2000). Strong ties are considered to have a positive influence on knowledge flows and social cohesion, though they have been observed to have an inverted U shape effect on innovation (Ruef, 2000; Phelps et al., 2012) as strong ties can lead to *too much* cohesion where nodes are so tightly interlocked that it becomes a hindrance to access different and novel knowledge. Molina-Morales and Martinez-Fernandez (2009) argue that networks with small number of strong ties and many weak ties are most conducive for knowledge sharing among clusters.

Proximity also influences knowledge related performances in inter-organisational networks. Geographical, cultural, and sectoral proximities influence how partners access knowledge in the network. Scholars highlight (Simonin, 1999; Sampson, 2007) that if partners have too similar knowledge resources, it results in little novel knowledge and if partners have too divers knowledge resource, it leads to difficulties in understanding partner's knowledge. Market overlap between partners also hinder knowledge sharing as organisations tend to be protective of their core knowledge, and not share it with their competitors (Baum et al., 2000).

Absorptive capacity is the ability of an organisation to identify and *assimilate* knowledge in partners (Cohen and Levinthal, 1990) It is a cumulative ability, since it depends on prior related knowledge and background diversity (Cohen and Levinthal, 1990; 137). Jane Zhao and Anand (2009) argue that absorptive capacity is a strong predictor of knowledge-related performances for networked firms. This stems from a firm's receptiveness towards novel knowledge and capabilities. If a firm is more receptive of knowledge beyond its organisational boundary that is residing in the network it would be more than likely to adapt such knowledge for its own contextual needs.

Absorptive capacity of an organisation can be enhanced through close cooperation with alliance partners. This can take form of exploration of novel ideas and knowledge in existing partnerships (Zollo et al., 2002). Though this process is dependent on alliance partner's willingness for knowledge transfer and absorption capacity (Jane Zhao and Anand, 2009).

### 2.7. Research Question

Following the discussion in preceding sections, it has become evident that tacit knowledge plays a critical role in encouraging innovation and facilitating access to novel knowledge for organisations in inter-organisational network. Various theories of inter-organisational networks discussed in 2.2 are all focused at an organisational level, and analyse the network in terms of organisations' ability to exploit other organisations for resources (knowledge) within the network. For instance, resource dependence theory describes the inter-organisational network as a resource and argues in terms of interdependence of firms within this network owing to their inability to access the resources they need. Similarly, organisational ecology discusses competition and constraints as two primary aspects of a network influencing organisations within. The resource based and relational view of the firm also presents competitive advantage as being determined at the organisational level and the network as a source of competitive advantage. Any organisation in a network can derive value from resource that are not fully owned or controlled by itself.

These theories are focused on an organisation's ability to exploit resources at an organisational level, e.g. through strategic alliances, joint ventures, and commercial partnerships. This ignores the role played by individuals in these networks. As discussion of network theory (social networks) has shown, social networks can not only act as source of competitive advantage, but certain networked individuals in such networks play a critical role in determining the outcome of tacit knowledge exchange process. This study will provide a framework to demonstrate the effect of these networked individuals. This leads to the following research question:

*Research Question: How can we demonstrate the effect of networked individuals with high tacit knowledge on organisational performance in inter-organisational networks?*

To answer the research question, this dissertation will make use of method triangulation, and use interviews, case studies, and social network tools to determine how tacit knowledge transfer takes place within inter-organisational networks, and how network composition and movement of individuals affects that process. This study will focus on firms involved in grand prix motor racing (Formula 1) to explore the research question and objectives. Formula 1 provides an appropriate setting to apply social network analysis tools to understand the research question.

# Chapter 3. Methodology

This chapter describes the research philosophy and methodologies and follows Saunders et al. (2007) research design approach as shown in the figure 4. These onion layers structure the thesis and provide a framework for research progression. Layers are discussed in more details in the following paragraphs.

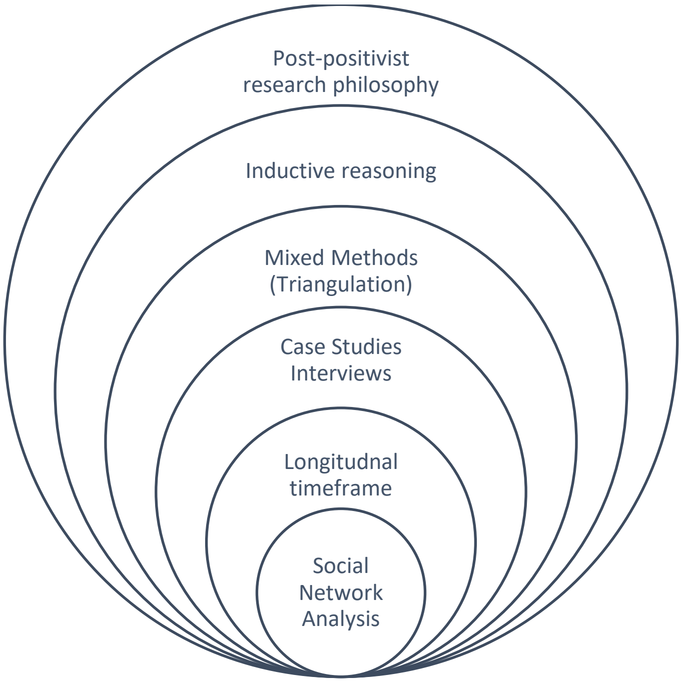



*Figure 4 Research Onion (adopted from Saunders et al. 2007)*

The first layer is that of post-positivist research paradigm. Collis et al. (2009) define the research paradigm as a philosophical construct that is used to conduct scientific research. The expansion of knowledge leads to development of new paradigms. Kuhn (1996) defines paradigms as universally recognised scientific achievement that for a time provide model problems and solutions to a community of practitioners.

The first paradigm to have emerged was *positivism* (Collis et al., 2009). Positivism has remained dominant for centuries and been *adequate* in providing a construct for scientific enquiry based in natural sciences. However, with the progress and development of social science research, a new paradigm has emerged, *interpretivism*.

Positivism is rooted in natural sciences and rests on the assumption that reality is singular and objective and is immune to changes through the act of investigation (Collis et al., 2009) Positivism research revolves around a deductive process that provides explanation of social phenomena. Collis et al. (2009) define interpretivism as arising from the criticism of positivism. Interpretivism advocates that reality is subjective and multiple as it resides in minds. The act of investigation affects reality. Interpretivist research involves inductive process aimed at providing an '*interpretive understanding*' of the social phenomena within a given context (Collis et al., 2009). Creswell (2007) categorised the main philosophical assumptions of two paradigms as shown in table 2.

Table 4 Assumptions of the main paradigms (adopted from Creswell, 2007 and Johns, 2010; 54)

| Philosophical Assumption | Positivism | Interpretivism |
|---|---|---|
| *Ontological assumption (nature of reality)* | Reality is objective and singular, separate from the researcher | Reality is subjective and multiple, as seen by the participants |
| *Epistemological assumption (what constitutes valid knowledge?)* | Researcher is independent of that being researched | Researcher interacts with that being researched |
| *Axiological assumption (role of values)* | Research is value free and unbiased | Researcher acknowledges that research is value ridden and biases are present |
| *Rhetorical assumption (language of research)* | Researcher writes in a formal style and uses the passive voice, accepted quantitative words, and set definitions | Researcher writes in an informal style and uses the personal voice, accepted qualitative terms and limited definitions |
| *Methodological assumption (process of research)* | Process is deductive<br><br>Study of cause and effect with a static design (categories are isolated beforehand)<br><br>Research is context free<br><br>Generalisation lead to prediction, explanation, and understanding<br><br>Results are accurate and reliable through validity and reliability | Process is inductive<br><br>Study of mutual and simultaneous shaping of factors with an emerging design (categories are identified during the process)<br><br>Research is context bound<br><br>Patterns and/or theories are developed for understanding<br><br>Finding are accurate and reliable through verification |

Both the paradigms discussed together form two extremes of a continuum and between these extremes exist many philosophical positions as described in table 3. The researcher's approach to enquiry is shaped by their culture and values. These social aspects prejudice every researcher toward the subject of the enquiry. To begin research, a researcher must identify a framework or methodology for enquiry. This framework consists of skills, assumptions, and practices that the researcher employs as he/she moves from his/her paradigm to the empirical world (Johns, 2010).

Table 5 Metaphysics of alternative paradigms (adopted from Guba and Lincoln, 1994 and Johns, 2010; 55)

| | Positivism | Post-positivism | Critical Theory | Constructivism |
|---|---|---|---|---|
| *Ontology* | Naïve realism – 'real' reality but apprehendable | Critical realism – 'real' but only imperfectly and probabilistically apprehendable | Historical realism – virtual reality shaped by social, political, cultural, economic, ethnic, and gender values: crystallized over time | Relativism – local and specific constructed realities |
| *Epistemology* | Dualistic/objectivist: finding true | Modified dualist/ objectivist: critical tradition/ community: findings probably true | Transactional/subjectivity: value mediated findings | Transactional/subjectivist: created findings |
| *Methodology* | • Experiments<br>• Statistics<br>• Simulation<br>• Survey | • Experiment<br>• Survey<br>• Case study | • Action research<br>• Feminist studies<br>• Case study | • Ethnography<br>• Grounded theory<br>• Phenomenological research<br>• Case study |

This research falls under a post-positivism paradigm following the multi-methodology approach. Ontologically, therefore this research falls under the critical realism category (table 3). Second layer of the onion highlights the inductive approach of this study and aims to generalise based on specific observations. This implies that while research will produce robust findings which can be applied to other suitable contexts, research findings will not be universally true. This is a realist approach and the findings are not universally true.

## 3.1. Triangulation of Methods and Research Strategy

This study adopts a multi-method approach, triangulating interviews, case studies, and social network analysis to answer research questions. Denzin (1978) defines triangulation as combination of methodologies in the study of the same phenomenon. Scandura and Williams

(2000) have argued that advantage of triangulation lies in that it can compensated for flaws present in individual methods and provide corroborating evidence from different methods.

Triangulation of methodologies is appropriate as this research falls within the post-positivist paradigm. Researchers in post-positivist paradigm maintained that using multiple methods allows the researcher to check of individual analyses (Connidis, 1983). This study uses interviews, case studies, and social network analysis to explore research questions. The following figure describes the research strategy.

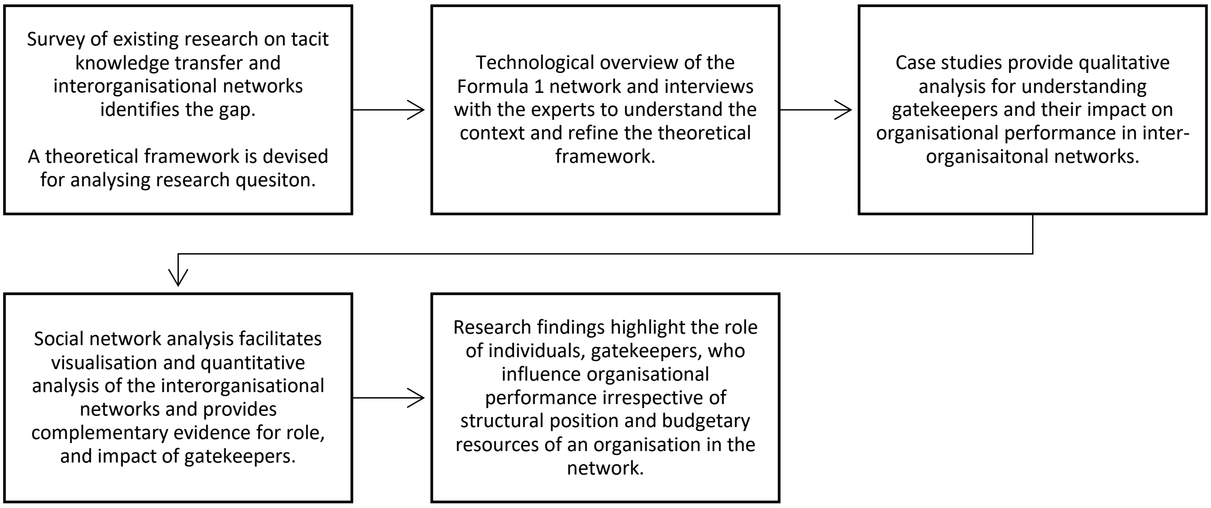



Figure 5 Research strategy diagram

Research strategy diagram establishes the progression of research problem from formulation stage in the literature survey to the research findings providing evidence for role of gatekeepers and their influence on organisational performance.

## 3.2. Interviews

Arksey and Knight (1999: 3) describe interviews as being concerned with exploring data on understandings, opinions, what people remember doing, attitudes, feelings and the like, that people have in common. This research used face to face semi-structured interviews with academics to explore the primary research objective. Semi structured interviews involve a questionnaire and other questions are developed during the interview, if need be. The use of interviews allows the study to provide an understanding of Formula 1 and the broader motorsport industry (Collis and Hussey, 2009). It also allows the exploration of issues which may be confidential and commercially sensitive (Easterby-Smith et al., 2012).

The interview questionnaire was designed based on the literature survey and incorporated aspects of knowledge transfer process and alliances [appendix 6]. The questionnaire deals with motivations behind alliance formation and knowledge transfer. The dimensions of knowledge transfer that emerged in literature were also explored in interviews as was the directionality of transfer and industry variables and their influence on knowledge transfer process.

#### *Analysing Interviews*

Robson (2011) has highlighted the primary challenge with analysing qualitative data such as interviews. In case of qualitative data, there is no universally accepted set of conventions for analysis corresponding to those observed with quantitative data. Collis and Hussey (2009) argue that qualitative data collection method can be incorporated into analysis.

This study uses labels and pattern identification to analyse the interview data. When using general analytical procedure for interviews, researchers give labels (based on literature) to phrases, sentences, and ideas as instances of a thing or idea which is relevant to the research. These labels inform and evolve with the data collection process and help focus analysis by facilitating pattern recognition. Using these patterns, this study has developed a set of generalisations which can be formalised in form of labels that are used for analysis.

These themes, based on the literature review, were found more appropriate in analysing the interviews and generating findings than nVivo, a qualitative analysis software. nVivo allows users to create "*nodes"* which can be then *"coded"* with interview texts. This process results in interview data being listed under different "*nodes*" which can be used for identifying patterns, classifying data, and modelling. The author carried out an nVivo based analysis, but the patterns identified were inherently biased as they were dependent on the classification of *nodes* as done by the author. This is not consistent with a post positivist approach. As a result, a literature review based framework was adopted.

### *Interviewees*

Interviewees were selected based on their expertise in Formula 1 and other motor sports. All three interviewees work at major research universities, and have published extensively on the topic of motorsports in reputed international journals and have worked/are working with Formula 1 teams on a range of issues. All interviewees have more than ten years of experience of working in motorsport research. The interviewees have not been involved in the author's supervision or assessment.

These interviewees help establish the relationship between knowledge transfer and individuals, provide context to research questions, and facilitate a robust analysis. The interviewees also highlighted the need for new labels in analysis as research progressed. This informed the case study and social network analysis and provided a consistent structure to the study.

## 3.3. Case Studies

A case study base research strategy provides particular strengths (Bebensat et al., 1987, cited by Voss et al., 2002; 197):

- The phenomenon can be studied in its natural setting and meaningful, relevant theory generated from the understanding gained through observing actual practice.
- The case method allows questions of why, what and how to be answered with relatively full understanding of the nature and complexity of the complete phenomenon.
- The case method lends itself to early, exploratory investigations where the variables are still unknown and the phenomenon not at all understood.

Scholars have pointed out that case study methodology needs to be systematic to be able to deliver rigorous results (Yin, 2003; Voss et al., 2002; Johns, 2010) as researcher, knowingly or unknowing, can introduce bias to results. Yin (2003) argues that researchers can overcome these challenges by relying on multiple sources for the data and systematic analysis of cases study findings.

Bryman and Bell (2015) and Voss et al. (2002) highlight lack of *generalisability* of case study findings. It is a challenge to extrapolate research findings of a single case study for broader applicability. Yin (2003) argues that case studies are in the neighbourhood of theoretical positions, rather than populations. Case studies allow for analytical generalisation and cannot be taken to represent a sample. Scholars (Eisenhardt, 1989, Voss et al., 2002; Yin, 2003) have argued that case studies are analogous to experiments, and therefore, by adhering to a systematic and analytical approach to different stages of case study, design, data collect, and analysis, researchers can alleviate most of the concerns associated with the methodology.

Case studies have been criticised as being *no more than a rich description of events* (Easton, 2000) and not grounded in firm epistemology. Yin (2003) argues that case study research belongs to phenomenological paradigm, but this is contrary to lack of an epistemological base. Therefore, for a case study to belong to post-positivist paradigm, it has to be systematic, rigorous in its inquiry into the underlying reality (table 3). Following this approach, a case study research can provide the researcher with causal explanation, especially of contemporary phenomena. Management and social science researchers have used case study research extensively (Barnes, 2001) and it meets the methodological standards of this study.

Reliability and validity are important at all stages of the case study research process and consequently, these dimensions are considered here before the distinguishable stages of the research process are discussed. Four tests have been commonly used to establish the quality of empirical social research, including case study research (see the following table).

Table 6 Tests for establishing quality of the case study research (adopted from Yin. 2003; 34)

| Test | Tactic | Applicable Phase of Research |
|---|---|---|
| *Construct Validity (Is case study measuring the concept that is focus of the research?)* | • Use multiple sources of evidence<br>• Establish chain of evidence<br>• Key informants to review draft reports (if possible) | Data Collection |
| *Internal Validity (how well the case study avoids confounding?)* | • Pattern matching<br>• Explanation building<br>• Time-series analysis | Data analysis |
| *External Validity (Extent to which case study findings can be applied to other contexts)* | • Use replication logic in multiple case studies | Research design |

| | | |
|---|---|---|
| *Reliability (Is the case study accurate, i.e. error free and unbiased)* | • Use case study protocol<br>• Develop case study balance | Data collection |

This research has used many documentary sources for data collection to ensure construct availability. Cases selected for analysis belong to different time in Formula 1 and provide balance to case study analysis. Certain key themes and patterns emerge from each case study and are documented to ensure validity and reliability of the findings.

### 3.4. Social Network Analysis

Social network analysis forms the core of the research onion and provides a quantitative foundation for this study. Graph theory and social network analysis facilitate a multi-level analysis (individual, intra and inter organisational, and network level). Research in this field is inherently multilevel, focusing on individual, intra-organisational, and inter-organisational nodes. Researchers in organisational behaviour have studied the influence of social networks on individual creativity (Burt, 2004); Hansen (1999) has investigated how the strength of interdivisional ties influence knowledge transfer within firms; strategy researchers have studied how inter-organisational network structure affects firm performance (Schilling and Phelps, 2007).

This study focuses on a systematic level of analysis for understanding the knowledge transfer process (Gupta and Govindarajan, 2000) in competitive-cooperative networks. This study had to balance the analysis along a) the structural attributes such as individual structural measures and whole-network measures, and b) relational attributes such as relational content, relational properties, (Burt et al., 1983; Marsden, 2005; Eisenberg and Monge, 1987). This is accomplished by using social network analysis metrics to analyse the network based on not only the existence of a link or relation between two individuals but also taking the institutional setting into account. This allows the study to explore multi-layered and interlocking knowledge transfer process within relationships in the network. Table 6 is a glossary of network elements.

Table 7 Network Glossary

| | |
|---|---|
| Node | A node (or a vertex or an actor) is the fundamental unit of a network. |
| Edge | An edge (or a link or a bond) connects two nodes. |
| Directed or Undirected | An edge can be directed, if it runs only in one direction that is from one node to another node. An edge is undirected if it runs in both directions. A network is directed if all its edges are directed (Newman, 2003) |
| Geodesic path | A geodesic path is the shortest path between a pair of two connected nodes (Newman, 2001) |
| Component | A component is defined as a subset of a network. Component to which a node belongs consists of nodes that are connected to it through edges of the network. |

This study is set in the context of Formula 1 and employs a set of mathematical metrics to explore relationships and movement of knowledge in the network.

Studies (Fromhold-Eisebith, 2004) have used social network analysis metrics to analyse innovative networks. Social network analysis metrics are being used in fields as varied as management sciences, organisational studies, economics, sociology, and network studies (Knoke and Yang. 2008). They provide an important mathematical tool to study knowledge transfer in a geographical dimension, human capital, and entrepreneurships, and inter-regional and intra-regional linkages (Fromhold-Eisebith and Werker, 2013; Grabher and Powell, 2005; Huber 2007; Kratke and Brandt, 2009; Murray, 2004). Metrics are also a useful tool to study how knowledge flows drive innovation in a network (Kratke, 2010).

The following test case demonstrates some core principles of social network analysis. This test case involves two teams, Team 1 and Team 2. In year 2000, Team 1 employs **A** and **B** and Team 2 employs **C** and **D**. In Year 2001, **B** moves to Team 2, and now Team 1 only has **A**.

Table 8 Test Case

| ***Year*** | ***Team 1*** | ***Team 2*** |
|---|---|---|
| ***2000*** | *A, B* | *C, D* |

| | | |
|---|---|---|
| ***2001*** | *A* | *C, D, B* |

The resulting network for year 2000 and 2001 is shown in figure 6.

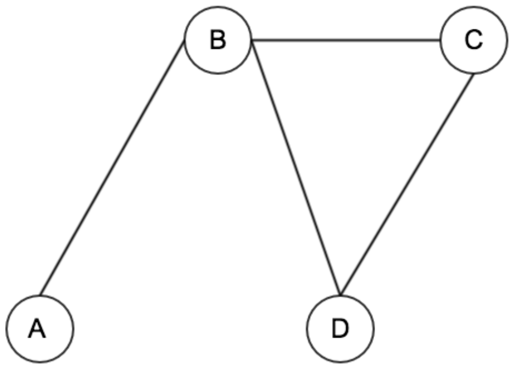



Figure 6 Network graph for test case 1

Table 9 contains network level metrics for the network shown in figure 6.

Table 9 Network level metrics for Test Case 1

| | |
|---|---|
| Nodes | **4** |
| Edges | 4 |
| Directed or Undirected | Undirected Graph |
| Component(s) | 1 |
| Average Degree | 2 |
| Diameter | 2 |
| Graph Density | 0.667 |
| Average Clustering Coefficient | 0.778 |

Table 10 shows node level metric values for each node in the network.

Table 10 Node level metrics for Test Case 1

| Nodes | Degree | Betweenness Centrality | Page Rank | Clustering Coefficient | Eigenvector Centrality |
|---|---|---|---|---|---|
| A | 1 | 0 | 0.141 | 0 | 0.461 |
| B | 3 | 2 | 0.367 | 0.333 | 1 |
| C | 2 | 0 | 0.246 | 1 | 0.854 |
| D | 2 | 0 | 0.246 | 1 | 0.854 |

Figure 6 shows a longitudinal network for year 2000 and 2001 where edges connect nodes that have either worked together in past or are working together in the present. Note that employee B is now attached to A, C and D since s/he has worked with them all at some stage during the time period under examination (2000-2001). All edges carry equal weight.

**Diameter**: Any given pair of connected nodes have *path length* of 1. The diameter of a network graph is the longest path length between any two nodes in the network. The average path length of the network is average path length between all pairs of connected nodes (Newman, 2003). The diameter of the network can give indication of the social nature of discourse (Albert and Barabasi, 2002). A large diameter implies a potentially loosely connected community; a small diameter may be a very densely connected community, or one in which few connections are present (most nodes unconnected or connected to a small number of other nodes). In the test case, figure 6, the diameter is 2. This implies that all nodes can be reached by another connected node following upto two edges (except for isolated nodes.) For instance, to reach node A from node D, there is path length of 2, D to B, and B to A.

**Density:** Density of a network is the ration between number of actual links in the network and number of all possible links. Density is structural property of the network and reflects the connectedness of the network (Tichy et al., 1979).

**Average Path Length** is defined as average path distance between all connected pair of nodes along the shortest paths (Albert and Barabasi, 2002; Newman 2003). In graph theory, average path length, clustering coefficient, and degree metrics are considered the most concrete measurement of network topology. Shorter average path length and higher clustering coefficient values indicated a small world phenomena and as such are of interest to scholars and to this study (Newman, 2003).

**Degree Centrality**: The degree of a node is number of edges that are adjacent to the node. A network with directional links has both an in-degree and an out-degree for each node, which are the numbers of in-coming and out-going edges respectively (Albert and Barabasi, 2002; Newman, 2003). In case of an undirected network, there are no in-coming or out-going edges as edges run in both directions. A node with high degree is highly connected within the network and potentially highly influential. Low degree of a node indicates that node is on the periphery of the network and potentially does not influence the information flows within the network. Degree can also be measured over whole network as the average degree of all nodes, including nodes with zero degree.

Nodes that have more links with other nodes may be in more advantageous positions because having more links, allow them to have alternative means to access and exploit the network, and be less dependent on other nodes. Having this ability to call on the entire network for their resource needs, puts them in an advantageous position vis-à-vis other nodes. In real life networks, nodes with higher degree are often third parties and gatekeepers (Mishra et al., 2017) and can benefit from this brokerage (Hanneman and Riddle, 2005). Degree is a simple but an effective measure of a node's power potential.

In the test case 1, average degree of the network is 0.667 which is considered very high for real life networks (Newman, 2003). Nodes with higher degree (may) have more power. Node B has a degree of 3 and therefore has more choices compared to other nodes, such as D and A. If node B wanted access to certain information, B can *acquire* that information either from A, C, or D whereas in case of D, only c and B are available, and in case of A, only B can provide information. Nodes with more links have more opportunities because they have choices (Hanneman and Riddle, 2005).

Though degree centrality approach can be misleading as having same degree does not (necessarily) make nodes equally powerful. Consider the following test case,

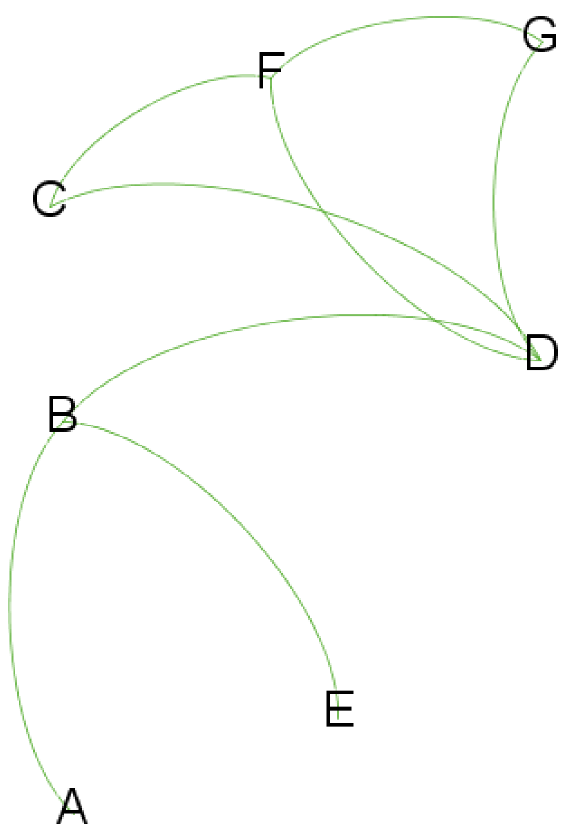



Figure 7 Network graph for test case 2

Compared to the test case 1, this network contains more nodes and edges. This affects the behaviour of network level as well as node level metrics. The following table lists network level metrics,

Table 11 Network level metrics for Test Case 2

| | |
|---|---|
| Nodes | **7** |
| Edges | 8 |
| Directed or Undirected | Undirected Graph |
| Component(s) | 1 |
| Average Degree | 2.286 |
| Diameter | 3 |
| Graph Density | 0.381 |
| Average Clustering Coefficient | 0.6 |

As can be seen in table 12, Node B and node F both have degree of 3 but as evident from the network graph (figure 2) Node B, apart from D, has links with A and E, which in turn are isolated and have one link each. Whereas node F is connected to C, D, and G which are connected to each other. This implies that F has access to more resources within that relationship triad.

Table 12 Test Case 2 Node level metric for Test Case 2

| Node | Degree | Betweeness Centrality | Page Ranks | Clustering Coefficient | Eigenvector Centrality |
|---|---|---|---|---|---|
| A | 1 | 0 | 0.070 | 0 | 0.264 |
| B | 3 | 9 | 0.229 | 0 | 0.780 |
| C | 2 | 0 | 0.158 | 1 | 0.855 |
| D | 4 | 9.5 | 0.206 | 0.333 | 1 |
| E | 1 | 0 | 0.070 | 0 | 0.264 |
| F | 3 | 0.5 | 0.157 | 0.667 | 0.802 |
| G | 2 | 0 | 0.110 | 1 | 0.590 |

A node is likely to be more influential if it is connected to other central nodes, as it would allow the node to *quickly* reach other nodes. It follows from this statement that if the node is connected to other well connected nodes, such as F, then those nodes are not dependent on the node F for influence and vice-versa. Bonacich (1972a, 1972b) argues that being connected to other well connected nodes makes a node central, but not (*necessarily*) powerful. Counterintuitively, being connected to other nodes that are not well connected makes a node powerful, because these other nodes are dependent on the node whereas in the case of other well connected nodes, they are not solely dependent on one node to access the network flows (Hanneman and Riddle, 2005). Bonacich (1972b) proposed that both centrality and power were a function of the connections of the nodes in one's neighbourhood. The more connections the nodes in your neighbourhood have, the more central you are. The fewer the connections the nodes in your neighbourhood, the more powerful you are.

**Average Clustering Coefficient**: The clustering Coefficient is one of the main statistical property used to describe large graphs (Watts and Strogatz, 1998). The clustering coefficient of a node (with a degree of at least 2) is the probability that any two random neighbours of that node are linked together. For the whole network, it is calculated as the average of clustering coefficients of all nodes with degree greater than 2 (Latapy, 2008). A clustering coefficient of 1 indicates perfect cluster, or a solid lattice structure, and 0 indicates a perfect random network with no clusters. Complex social networks tend to exhibit a high degree of clustering. In the test case 1, average clustering coefficient of 0.778 reflects higher probability of two random nodes being linked together, whereas in test case 2, a *more complex network,* has average clustering coefficient of only 0.7, highlighting that complex networks do not necessarily have higher clustering.

**Betweenness Centrality**: Betweenness centrality is a node based centrality metric in social network analysis. The betweenness centrality of a node is number of geodesic paths on which the node appears, normalised by total number of geodesic paths (Freeman, 1977). It can be calculated for both directional and unidirectional links. Betweenness centrality highlights nodes that are in *favoured position to the extent* that the node is on the geodesic paths between other pairs of nodes in the network (Hanneman and Riddle, 2005) This implies that the more other nodes are depended on a particular node to make connections with other nodes, the more influence the node has.

As evident from the test case 1, node B lies either between each other pair of nodes or there is also a path going through B even if two nodes are directly linked. So if B wants to contact D, B can do so without going through any other node, but if D wants to contact A, D has to go through B. This study used a unidirectional algorithm (Brandes, 2001). A node with high betweenness centrality has high influence over the transfer of information or items through the network.

The influence of a node is reduced if the node is not present on all geodesic paths connecting any given pair of nodes. For example, consider test case 2. Nodes B and F have same number of edges (degree), 3 but between centrality of F is 0.5 whereas B has a betweenness centrality of 9. As it can be observed from the network graph, while F is present on geodesic path between C and G, but there is also another geodesic path between C and G, G -> D -> C which do not pass through F. Whereas in case of B, any path connecting node pair A and E, A and D, and D and E has to pass through B, and so the betweenness centrality of B is highest, and puts it in a central position vis-à-vis other nodes and exercise control over information flow between those node pairs.

Freeman et al. (1984) argue that betweenness centrality highlights nodes with positional advantage to the extent that they are on the geodesic pathway between other pair of nodes, that nodes who are “between” other nodes, and on whom other nodes must depend to conduct exchanges, will be able to translate this broker role into power. This can be observed in a network where two nodes want to engage in a relationship, but the geodesic path between them is rendered inaccessible due to a reluctant node or gatekeeper (Mishra et al., 2017). In such a scenario, if there exist another geodesic path, the node pair is likely to use that pathway, even if it is longer and not convenient.

**Eigenvector Centrality**: Eigenvector centrality is a metric which incorporates the importance of the other nodes to which a node is (directly) connected. This approach forms the mathematical basis of the page rank algorithm which formed the core of the original Google search algorithm (Page et al., 1999). Bonacich (2007: 555) argues that ‘…*eigenvector centrality is designed to be distinctively different from mere degree (centrality) when there are some high degree positions connected to many low degree others or some low degree positions are connected to a few high degree others.*’ Since network structures in this study comprise of nodes with a varying degree of degrees, eigenvector centrality is a particularly important metric.

In larger and more complex networks than the examples discussed earlier, this measure can be misleading. Consider a large network, and two nodes, X and Y. Node X is part of a cluster within the larger network, and is quite far from other nodes in the network. Node Y on the other hand, is at moderate distance for all other nodes in the network. In such a scenario, *farness measures* will be of similar magnitude for Node X and Y but within the network, Node Y is more *central* than node X as Y is able to reach more nodes, with shorter path lengths.

Nodes with higher eigenvector centrality are like node Y. These nodes are the most central nodes that is with smallest *farness* from other nodes when these distances are considered at the network structure level. These nodes do not have to be dependent on local nodes, or clusters for that matter, to access novel knowledge and information, as they can access information and knowledge from distant nodes and clusters due to short path lengths to those nodes.

Eigenvector centrality is calculated via factor analysis. A detailed discussion of factor analysis is beyond the scope of this study but a short introduction follows. Factor analysis helps to identify the *indicator* or *dimension* of the distance among nodes. Position of each node within the network with respect to each dimension is called its *eigenvalue*, and the set of *eigenvalues* is called *eigenvector*.

### 3.5. Small World

Small world tendency of a network is observed by a high clustering coefficient and short path length (Newman, 2001; Newman, 2003; Steen et al., 2011). The following figure shows small world network compared to a regular network and a random network.

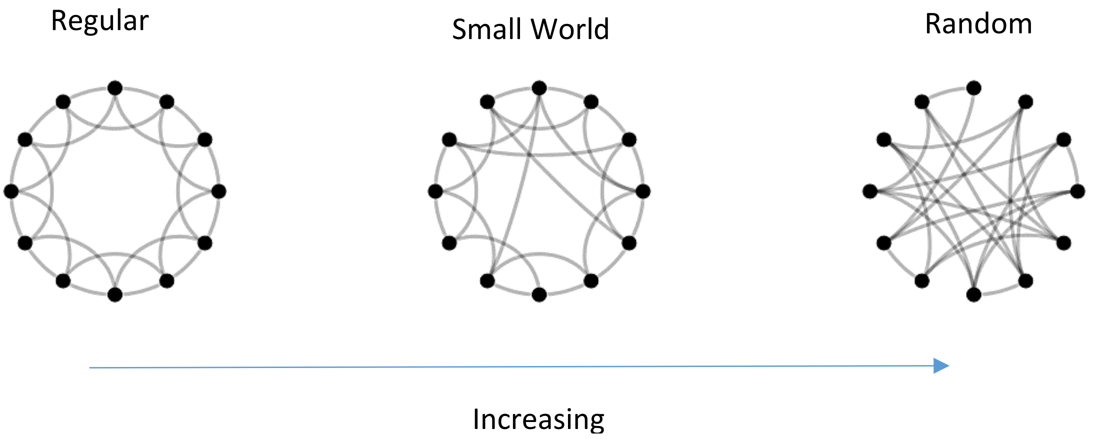



Figure 8 Regular, Small World, and Random Networks (adopted from Watts and Strogatz, 1998)

In the figure, the middle configuration of nodes and edges represent a small world network that has high clustering coefficient and short path lengths. It differs from the random network and regular network in that neither all of its edges are randomly connected nor are they regularly laid out.

As discussed in preceding sections, clustering coefficient is a measure of probability of any two nodes being linked together, forming a triangular relationship within the network. This implies that in a highly clustered network, two nodes connected through a third node, are highly likely to be directly connected forming a triangle (Newman, 2001; Steen et al., 2011).

Path length is the average number of edges between all nodes within a network. Observations can be made about small world nature of a network by comparing clustering coefficient and path length with a *corresponding* random network of the same number of connections and nodes. The small world coefficient $Q$ is defined as the ratio of clustering ratio and path length ratio (Easley and Kleinberg, 2010; Albert and Barabasi, 2002; Boccaletti et al., 2006; Watts and Strogatz, 1998);

$$Q = \frac{Clustering\ Ratio}{Path\ Length\ Ratio}$$

(Equation 1)

where;

$$Clustering\ Ratio = \frac{Clustering\ Coefficient\ of\ the\ Actual\ Network}{Clustering\ Coefficient\ of\ the\ Corresponding\ Random\ Network}$$

(Equation 2)

$$Path\ Length\ Ratio = \frac{Path\ Length\ of\ the\ Actual\ Network}{Path\ Length\ of\ the\ Corresponding\ Random\ Network}$$

(Equation 3)

The clustering coefficient and path length of the corresponding random network can be calculated by using following equations,

$$Clustering\ Coefficient\ (Random\ Network) = \frac{Number\ of\ nodes}{Number\ of\ Connections}$$

(Equation 4)

$$Path\ Length\ (Random\ Netwokr) = \frac{\log Number\ of\ Nodes}{\log Number\ of\ Average\ Connections}$$

(Equation 5)

If the network has high levels of clustering and short average path length, the network could be described as a small world (Watts and Strogatz, 1998).

### 3.6. Social Network Analysis Data

This study used *Who Works in F1* guides, to construct a longitudinal database of Formula 1 team employees from 1992 to 2001. The database was coded to identify, for each year, individuals working within a team as *nodes* and the team as the *edge* connecting all these nodes.

This database was run through a python script (appendix 1) to generate a Gephi compatible input file. Gephi was used to run simulations and algorithms to allot a metric value to each individual in the network. This process was repeated for the period of 1992-2010, treating all links monotonically as outlined above. Thus, nodes in the graph represent individuals and the (unweighted) edges denote that the connected individuals worked in the same team for at least some time over the period 1992-2001. This study proceeds with the assumption that edge exists between any two nodes if they have worked together in a team. This assumes that edges are the only way of knowledge flow. In real life, there are other way for tacit knowledge transfer, such as observation or conversation informal interaction between individuals who are not working within the same team. But the nature of Formula 1 teams, tightly bounded and tendency to keep technological advances secret, highlights difficulty in tacit knowledge transfer through the other routes.

This study also allots the same edge weight, 1, to all connections. While an analysis with weighted edges could be done, where edges between a pair of nodes could be ranked based on standards such as their past links and points the team performances while the pair of nodes are working in the team. This was deemed impractical for two reasons, the first being that there is no objective standard, other than the one researcher chooses, for allotting weighs to edges, and second, this will also result in qualitative categorisation of edges, such as links between a technical director and driver will be distinct from link between driver and race engineer, and the weighing scale would need to be devised for each *category*. Both approaches would result in bias. Therefore, each edge was allotted the same weight, and analysis was centred on centrality and topological (network wide) metrics.

This analysis resulted in centrality metrics, degree, betweenness, eigenvector, and page rank centrality and network wide metrics, path length, clustering coefficient, density, and diameter. Centrality metrics provided a profile for each individual node in the network and network wide metrics contextualised those findings.

### 3.7 Literature Survey: Databases and Keywords

The author used the following research databases,

- Google scholar
- University of Bath Library
- Scopus (for author profiles and journal ranking based on SCImago)

The following keywords were used to find relevant papers; *social networks, social network analysis, knowledge, knowledge transfer, tacit knowledge, tacit knowledge transfer, knowledge transfer and innovation, strategic alliances and knowledge transfer, absorptive capacity, core competencies and knowledge transfer, prior alliances and knowledge transfer, centrality metrics, python.*

### 3.8 Ethics Statement

No conflicts of interest were identified.

# Chapter 4: Context: Formula 1 - A Small World

This chapter discusses the context for this study. It begins with a technological overview of Formula 1 and how it has evolved over the decades. This discussion highlights the unique inter-organisational network of the Formula 1 for carrying out network analysis to understand tacit knowledge transfer and role of individuals in that process.

The next section discusses small world networks, which are conducive for innovation and high knowledge flows, as is the case with Formula 1 and provide a summary of literature on the topic and its relevance to this study.

## 4.1. Technological Overview of Formula 1

Formula 1 faces a pace of technological development and logistical challenges similar to businesses such as information management systems, pharmaceutical industries, and aerospace manufacturers where firms form alliances with their competitors to tackle specific projects, expand their resource base, and overcome regulatory change. Smith et al. (2007) identify these as ideal conditions for fostering knowledge transfer.

In context of Formula 1, knowledge transfer, and more specifically tacit knowledge is of central importance. Aversa et al. (2015) highlight the unique the business model of Formula 1 which involves trading and selling both technology and human resource with the competitors and reflects the important role played by tacit knowledge in this process. This study is focused on exploring mechanisms for tacit knowledge transfer and its effect on organisational performance. To this end, it is important understand the evolution of the context of the study, that is Formula 1 racing and its evolution over the years.

The following table lists a series of key technological discontinuities in Formula 1 history. This is followed by a technological overview of Formula 1.

Table 13 Technological discontinuities and regulation changes (adapted from Jenkins, 2010: 888)

| Season | Technological discontinuities and regulation changes |
|---|---|
| 1954 | Fuel injection in Mercedes 196 Streamliner |
| 1955 | Disc brakes in Connaught Type B (Syracuse Grand Prix, Italy) |
| 1955 | Rear engine Cooper Climax |
| 1957 | Fuel Regulations |

| | |
|---|---|
| 1961 | Engine capacity reduced to 1.5 litre to encourage Formula 2 entrants to participate in Formula 1. |
| 1962 | Stressed monocoque chassis |
| 1966 | Turbo-charged (or supercharged) engines allowed with 1.5L capacity, and normally aspirated engines with 3.0L. |
| 1970 | Lotus T72 with side-mounter radiators, rear wings, torsion bar suspension, and inward located brakes |
| 1977 | Renault introduced turbocharged RS01 |
| 1981 | Reinforced *survival cell* made mandatory. Ground effect skirts banned. |
| 1989 | Turbo engines and refuelling banned. Engine capacity increased to 3.5L V10. |
| 1994 | Automated driver aids removed. |
| 1998 | Maximum width of cars reduced, use of slick tyres banned. |
| 2001 | Re-introduction of traction control |
| 2009 | Kinetic energy recovery system (KERS) introduced. |

These discontinuities are explored in more detail in the following sections.

### 4.2. Early Days: 1950-1970

*"Paradigms are universally recognized scientific achievements that, for a time, provide model problems and solutions for a community of researchers."* Thomas Kuhn (1996, pg. X)

In the 50s, a Formula 1 car had a large capacity engine in front of the driver and a rear-wheel drive. Performance of the car revolved around the engine (Jenkins, 2010). It was the paradigm of grand prix car development (F1 Atlas). Supercharged engines were a norm during that time. Normally aspirated engines were limited in capacity to 4.5 litres whereas supercharged engines were capped at 1.5 litres. A typical chassis of the time was a tubular frame construction with fuel stored behind the driver. In a tubular frame construction, components like engine and suspension are attached to a skeletal frame of tubes with body of the car not serving any function in structural integrity of the vehicle. Engines in these early cars were placed in front of the car, that is in front of the front axle of the car.

Alfa Romeo 158 and 159 were the most successful cars in 1950 and 1951 seasons and became a benchmark for other constructors. British team, BRM designed BRM15 to compete with the Alfa Romeo. Their car was built following the then norm of tubular frame chassis construction.

BRM15 had a 1.5 litre engine with 16 cylinders; capable of delivering 615 BHP at 12, 000 rpm. The car was never quite able to achieve its peak performance, mainly because of absence of a fuel injection system and its reliance on carburettors.

A carburettor is a device that works on Bernoulli's principle and delivers air and fuel mixture (in correct ratio) for combustion in the cylinder of an internal combustion engine. A fuel injection system is computerised and sprays fuel into the cylinder at regular intervals and the air is delivered separately via a throttle valve which opens on depressing the accelerator. A fuel injection system allows for more precise control, better fuel consumption performance, and accurate tuning to match driving conditions. Compared to carburettors, fuel injection systems are more complex and expensive. Formula 1 teams adopted this technology, irrespective of complexity and costs involve, for the performance gains.

Following the FIA's decision to switch to 2-litre Formula 2 regulation, Ferrari pulled ahead in 1952 and 1953 with Type 500 and Type 553. Ferrari cars were developing power close to 190 HP, which was unusual for the time. Maserati engine delivered even more power, 200 HP reaching 100 HP per 1000 cc of cylinder capacity; but they could not win the world championship. 1954 season saw introduction of 2.5 litre formula. Mercedes with their car, 196 Streamliner brought an eight-cylinder engine with direct fuel injection and laid the engine on its side to keep the centre of gravity as low as possible (Lawrence, 1998). This started the decline of the carburettor-based engines, such as the one used in BRM15. In the early phases, the Bosch direct injection system dominated Formula 1 but eventually made way for an indirect manifold injection system. Though the revolutionary air-valve controlled fuel injection of Renault was still 30 years away, fuel injection systems controlled by camshafts had arrived in Formula 1 (Wright and Matthews, 2001) and greatly improved fuel efficiency and driving dynamics of the Formula 1 cars.

Another invention to make its appearance in 50s decade was that of disc brake. (Jones, 1996) Formula 1 was populated by drum brakes so far and it was an English Dentist, Tony Brooks, of the British Connaught team who introduced disc brakes to the Formula 1. He won the Syracuse Grand Prix in Italy in the year 1955. Though the race did not have World Championship status, disc brakes had arrived on the grand prix circuits. It still took some time for the disc brakes to become widely adapted in Formula 1 but their utility was clear to all the constructors (Wright and Matthews, 2001). In 1958, during the Italian Grand Prix practice session, Ferrari mechanics removed the disc brakes from one of their sports cars and installed them on their Formula 1 cars. This illustrates the tendency of Formula 1 constructors to adopt *what works* and then evolve it into a more comprehensive solution.

In July of 1955, a truly radical innovation made its presence felt in Formula 1, the repositioning of engine from the front of the car to the rear of the driver. British teams were responsible for this radical change. One of these British manufacturers was Cooper Car Company, run by Father-Son duo Charles and John Cooper, who were described as '*cunning blacksmiths'* for their ability to source components from unusual places (Lawrence, 1998). They constructed chassis for their cars from the suspension components from Fiat Topolino, scrap materials from air raid shelters, aircraft and boat engines (Lawrence, 1998). Cooper was using motorbike engines with a short chain drive to rear wheel, located in a 'mid position', directly behind the drivers in their cars (Jenkins, 2010; Jones, 1996).

These cars turned out to be successful and Cooper progressed to Formula 2 where they started competing against Formula 1 manufacturers with the bigger 4.5 litres engines. In their very first race, British built Cooper Climax, with Sterling Moss as the driver, beat the works Ferrari's factory team. This was the first instance of a mid-engine Formula 2 car winning a Grand Prix. Another British manufacturer, Lotus, entered the Grand Prix championships in the same period with front-engine cars but didn't find much success till they switched to Cooper's idea of 'mid-engine' cars in 1960 with Lotus 18 (Crombac, 1986). Lotus founder Colin Chapman explained his design philosophy as '*wind cheating*' (Chapman, 1958). Chapman evolved the design process of the car around the chassis instead of engines, as was the norm among the contemporary Italians constructors such as Ferrari.

In 1955 British Grand Prix at Aintree, England, first mid-engine car made its debut in Formula 1 with Jack Brabham in Cooper-Bristol T40. The T40 was fitted with a 2-litre 'Bristol' engine that was mounted behind the driver. Within matter of few years, this design philosophy was so successful that front mounted engines became a thing of past demonstrating Formula 1 team's willingness to adopt innovations that work in a short period of time.

Fuel regulation came into effect after 1957. Before that, teams were free to choose what fuel they used. Peter Wright (Wright and Matthews, 2001) describes the practice of constructors adding various chemical compound to the fuel in 50s "*...teams were relying on the dark magic* *of various concoctions*." With the pressure from oil sponsors like Shell, FIA made it mandatory for the cars to use 'commercially' available variant of fuel. Between 1958-60, FIA regulations demanded use of aviation fuel with an octane rating of 130. The idea behind this move was to make Formula 1 more relatable to the fans and ordinary viewer. This forced Formula 1 teams to work closely with fuel suppliers to optimise fuel consumption, and consequently, improve fuel effecieny.

Until the mid-50s, automotive manufacturers had dominated motor sports and used it as testing bed for innovation but that changed after 60s with ***the advent of the networks of constructor*** organisations and sponsors and manufacturers (Foxall and Johnston, 1991). Setright (1973; 242) describe these changes, *"...the centre of the motor racing world had shifted from Italy to Britain, where specialist chassis- building teams used off the shelf engines and transmissions supplied by specialists. Only Ferrari and B.R.M. of the regular runners were left building their own chassis, engines and gearboxes, and the new era of the Formula 1 'special builders' had arrived*. "

The change in the centre of gravity of the motor racing combined with the change in regulations championed and encouraged by the companies looking for wider public awareness and aspiration for their products through the association with the motor sports, changed the sports in fundamental ways (Forxall and Johnston, 1991). The racing cars were now the result of a combined effort from a group of specialists employed within the automotive industry supplying specialist products and needs (Nye, 1986). Relative uniformity in the car designs of early 60s was challenged with the arrival of new teams like Lotus, who forced the industry to focus on 'continuous development of components' – tyres, electronic ignition systems, fuel injection, improved spark plug technology, monocoque chassis design, and aerodynamic efficiency (Foxall and Johnston, 1991). 1960's season also saw engine capacity reduced to 2.5 litre normally aspirated engines. This advent of a network of constructors working with alliance partners to produce a racing car highlights Formula 1 teams' need for specialist knowledge and technology.

The inaugural season of 60s began with two fatal accidents. Drivers Christ Bristow of Cooper and Alan Stacey of Lotus lost their lives in an accident during the Belgian Grand Prix at Spa. Christ Bristow lost control of his car and did not survive the resulting cartwheeling whereas in case of Stacey, a bird flew into his face and he got off the track resulting in a collision. These accidents highlighted how Formula 1 remained a dangerous sport and *needed more regulation* (Jenkins, 2010). To tackle this, FIA brought down the capacity of cars from 2 litres to 1.5 litres in 1961. However, it took another eight years for FIA to introduce helmet visors, which could have prevented accidents like that involving Alan Stacey. FIA also brought in another rule stipulating that cars only use commercial grade fuel with an octane rating of 100 or lower. This was done under the pressure of oil suppliers like Shell. This led to further innovation in Formula 1 as constructors responded to regulation changes. In fact, this process of regulation driving innovation repeats itself in Formula 1. For FIA's every change in rules and regulations constructors come up with their own innovation to work around them. FIA regulatory changes forced constructors to look for novel knowledge and technologies in the inter-organisational network of Formula 1 and innovate.

Cooper started the decade with their car Type T53 Cooper Climax. They won the World Championship of 1960. Type T53's mid engine design and 240 HP 4-Cylinder engine powered the car to and beyond 300 km/h. The time of front engine cars was finished for good. Ferrari went to great length to dismiss this new design 'paradigm' by calling British constructors as '*garagistes*' and '*assemblatori*' and remarking that horses have always pulled, and not pushed, the cart (Couldwell, 2003. Beck-Burridge and Walton, 2000. Nye, 1977). But with change in the rules focussing on the smaller powertrains in the early 60s, chassis technology became the new focus of innovation. Rules were changed partly to encourage participation of new entrants from F2 to compete in F1 (Jenkins, 2010). FIA reduced engine capacity to 1.5 litre (normally aspirated engine). Ironically, Ferrari followed the path as shown by the *garagistes* and built a mid-engine car using a V6 engine, which gave them the world title in 1961. Cooper and Porsche cars could not keep up with the 190 HP, 6-cylinder engine of Ferrari. Next few years saw the mid-engine design philosophy becoming the norm in Formula 1.

1962 season saw introduction of *stressed monocoque chassis*. Unlike tubular frame construction, in monocoque construction, loads are carried by the body's skin. Throughout the 1950s and early 60s tubular steel spaceframe dominated the chassis design of Formula 1 cars (Smith, 2012). But with the FIA bringing down the engine capacity to 1.5 litres, designers started putting greater emphasis on the chassis (Jenkins, 2010). Colin Chapman introduced Lotus 25 that employed riveted monocoque structure in which aluminium skin carried the structural load. Chassis and body formed a single integrated structure as it does in an aircraft

(Smith, 2012), and this highlights willingness of Formula 1 constructors to seek knowledge and technologies in completely different industries to their own for competitive advantage.

The riveted monocoque structure was lighter and possessed more torsional rigidity than the traditional tubular frame structure. Following year, Jim Clark won seven out of ten Formula 1 races for Lotus in the new car. For next few seasons Lotus dominated the Formula 1, with 19 wins out of the 39 Grand Prixes between 1962 and 1965.

By the end of 1965 season, engine power had risen to 220 HP with a rise in number of cylinders. 1966 season saw the introduction of 3-litre formula in the grand prix; Ferrari and Honda introduced 12-cylinder cars. Coventry Climax had constructed a 16-cylinder engine, however it could never see the starting grid because of issues with camshaft. BRM introduced a 16-cylinder engine car, BRM P83 that developed 400 HP but failed to win single grand prix due to recurring problems with the engine. Lotus used the same 16-cylinder BRM engine in Lotus Type 43 as a stopgap while working on the DFV's development. Driver's championship was won by Jack Brabham despite his Brabham-Repco car's 8-cylinder engine only producing a '*meagre*' 320 HP at 7500rpm, which was lowest output of any car on the circuit. Brabham's car though had superior handling it stayed ahead of the grid in the corners.

4$^{th}$ June 1967 saw the arrival of Double Four Valve (DFV) type Ford V8 engine. DFV was a result of collaboration between Lotus, Cosworth Engineering, and the Ford company, who funded the project. Even though Brabham won the championship in 1967 (it was Jack Brabham's team mate, Denis Hulme) The DFV type Ford V8 driven by Jim Clarke won the very first race it took part in at Zandvoort (Dutch Grand Prix). The DFV V8 engine would go on to dominate the Grand Prix racing cars till the advent of turbocharged cars and to date remains one of the most radical innovations in Formula 1 (Floyd and Jenkins, 2001). The engine was developed in response to the new regulations on engine size. DFV was a huge step in technological innovation. Chapman designed Lotus 49 around the DFV engine and employed it as a major part of the structure to reduce the weight and make car lighter (Floyd and Jenkins, 2001). Ford did not award Lotus with the exclusive rights for use of the engine, and made it available to other teams in F1. McLaren and Matra were the first teams to take advantage of this in 1968 using the Ford Cosworth DFV and Brabham followed in 1969. This led to the era of 'Ford powered kit-cars' in 70s where Formula 1 became dominated with Cosworth DFV engine, gearboxes manufactured by Hewland Engineering (Beck-Burridge and

Walton, 2000) and chassis and suspension designed by the constructors. Arrival of DFV 'kit cars' also put the vertically integrated constructors such as Ferrari and BRM who built their own engines and gearboxes at a disadvantage since kit cars were more cost effective.

Next year saw introduction of wings to Grand Prix (Jones, 1996). Aerodynamics finally made its presence felt in the car design. It started as little stumps at the front and rear of the vehicle at Spa- Francorchamps, Belgian Grand Prix. But within a month, engineers started using inverted wing surfaces on the struts at the back. At that time aerodynamics was still in the '*dark magic*' state and needed more research before it could be truly exploited by the constructors (Wright and Matthews, 2001).

Table 14 Impact of individuals on organisational performance 1950 -1970

| **Discontinuities in the Network** | **Individuals** | **Impact on Organisational Performance** |
|---|---|---|
| Mid-engine cars, fuel regulation changes, advent of networks of constructors (1958) | Charles and John Cooper/Jack Brabham | World championship in 1959 and 1960 challenging the domination of Ferrari and Alfa Romeo |
| Continuous development of components – tyres, electronic ignition systems, fuel injection, improved spark plug technology, stress monocoque chassis design, and aerodynamic efficiency, Ford-Cosworth DFV engine (1960 – 1967) | Colin Chapman (Lotus)<br>Keith Duckworth (Cosworth) | Lotus won four world championships between 1960 – 1970 against established teams such as Ferrari, BRM, and Cooper.<br><br>Following the introduction of DFV engine in 1967, the next seven consecutive world championships were won by teams using the DFV engine. |

It is evident from this discussion that new knowledge and technical changes such as repositioning of the engine from front of the car to middle, introduction of disc brakes, Cosworth's Dual Four Valve engine, or Lotus's riveted monocoque structure with load bearing aluminium skin were introduced by individuals in pursuit of more performance and competitive advantage.

### 4.3. Innovation in Action 1970-1989

In 1960s Colin Chapman had established himself as an innovative constructor with his monocoque design in early 60s (Crombac, 1986), which remains universal and indispensable to this day. His collaboration with Ford and Cosworth, and resultant DFV engine had been very successful. Chapman was about to introduce another radical innovation to Formula 1.

A common design philosophy had taken root among Formula 1 constructors when it came to designing intake for their normally aspirated engines. Intake was located in the nose of the car. Colin Chapman took a radically different approach to this, he decided to adopt solutions from aerospace industry and make car more aerodynamic. He did away with the nose intake and instead relied on a pair of radiators forming the sides of the car (Jones, 1996). This gave Lotus 72 an advantage; it could travel 14 km/h faster on long straights than its predecessor 49C (Atlas F1) with the same engine. Chapman also used torsion bar suspension (Wright and Matthews, 2001) and located the brakes inwards to further reduce the unsuspended mass and improve the handling of the car. It also had an overhanging rear wing to provide aerodynamic grip to the car.

At Zandvoort, Dutch Grand Prix on 21st June 1970 Jochen Rindt raced the Lotus T72 and won the race. Rindt went on to win three more Grand Prix, French, British and German. Later in 1971, Colin Chapman introduced another technological innovation to Formula 1, perhaps not quite as successful as his other innovations. His Lotus 56B was not powered by an internal combustion engine but by a Pratt & Whitney developed gas turbine engine. The engine was developed for locomotives and helicopters and was proved to have an exceptionally bad fuel efficiency. It required almost 100 litres of fuels for every 100 km, the driver sat forward in the car due to the length of the turbine and there was a considerable lack in the application of the accelerator and actual power delivery. It made cornering almost impossible for the drivers and put high demands on their skills. (Wright and Matthews, 2001)

Ferrari had merged with Fiat in 1969 and that provided the team with cash injection needed for research and development of a new flat 12-engine. The new engine provided some performance boost for Ferrari in 1970 but could not keep up with the DFV powered cars. After the merger with Fiat, Ferrari had built a Formula 1 test track in Fiorano, Italy in 1971. At Fiorano, Ferrari developed their new car, 312T that used the ‘flat 12-engine’ and a transverse gearbox. They tested the car extensively for speed and reliability and introduced it in 1975 season. Nikki Lauda won the world championship that year for the Ferrari. This illustrates the importance of automotive manufacturers, financial resources, and availability of research facilities for Formula 1 constructors. To gain competitive advantage, novel knowledge and technologies are needed, and either a team, with considerable financial investment, can develop new technologies and solutions, or acquire knowledge through means of alliances, as Lotus did in its alliance with Cosworth and Ford.

The French team, Tyrrell did try something radical in 1976 with their P34 which had two conventional rear drive wheel and four wheels in the front. Though P34 did win two races Tyrrell did not race the car in the next season, as there was no clear advantage of having six wheels over four. But a major technological change was around the corner.

Formula 1 teams have avoided the use of turbo chargers. The primary reason for this reluctance was the lag between pushing the accelerator pedal down and the actual power delivery. Turbo could have been potentially of benefit on long ‘straights’ but not with the ‘lag’ (Henry and Brinton, 1988). Race cars need instant delivery of torque to accelerate faster than the competitors. Nonetheless, Renault introduced the first car with a turbocharged engine in 1977. This marks one of the first times that a manufacturer entered Formula 1 with explicit purpose of developing and promoting an automotive technology for adoption in road cars (Henry and Brinton, 1988).

Though Formula 1 has seen supercharged cars in 1951 for a brief time, this was the first attempt in the last two decades. Jean-Pierre Jabouille was driving Renault and was not competitive in the race mostly due to the unreliability of the turbochargers. It took the team few more attempts before they could run the car competitively. And eventually Renault went on to win two Grands Prix.

Colin Chapman was working on his Lotus 78 in the late 1970s. It turned out to be another radical innovation to come out of Lotus. The Lotus 78 was revolutionary (Jenkins, 2010; Wright and Matthews, 2001) Peter Wright, the Lotus designer, designed it with the help of a wind tunnel and made use of aerodynamic principles to generate grip while cornering.

Aerodynamic principles had been used in Formula 1 in past in form of an ‘inverted wing’ and ‘spoilers’. The Lotus 78 made use of ‘ground effect’ to generate grip instead of only relying on the inverted wing. Peter Wright (2001, pg 299), defines ground effect as the effect that ground imparts to the free-air aerodynamic characteristics of a body moving through the air. In the case of a bird like a swan or a fixed wing aircraft, ground effect increases the lift at a given incidence and reduces the induced drag. This increase in aerodynamic efficiency enables the swan to accelerate in ground effect to a speed where flight away from the ground is possible. Lotus 78 had strips or skirts mounted between the wheels along the sides of the car that reached down to the tarmac, and these strips accelerated the wind flowing underneath the car to such an extent that a suction effect (or ‘inverse’ ground effect) was created.

This resulted in more grip for the car and it could turn the corners at incredible speed. It took Lotus about a year to mature the concept, and Lotus driver Andretti won the championship in 1978 in Lotus 79. Andretti and his teammate, Ronnie Peterson dominated the Formula 1 circuits that year. This again illustrates teams’ willingness to innovate and adopt solutions from other industries to gain competitive advantage.

The same year also saw the arrival of Gordon Murray’s BT46 which did away with radiators all together. The South African, working at Brabham was trying to create an aerodynamically symmetrical vehicle without radiator boxes to interrupt the airflow. He instead devised the idea of using heat exchanger tiles that were stuck to the body of the car. Though the system worked in theory, car couldn’t cope even in the tests and engine went much higher over the advised operating temperature. As a result, team had to cut holes right into the body of the car.

80s began in this environment of technological innovation and growing popularity of the sport. Twenty teams were competing for the title and with lap times being reduced on an average of three second from last year, and the race for technological superiority had begun in earnest. Ground effect was truly making the sport faster and cornering speeds had risen to a point where transverse acceleration rose to almost 3Gs (drivers experience a rise in their bodyweight as a consequence of (de)acceleration under heavy braking or high speed turns, Wright and Matthews (2001). The  physical impact on the drivers in corners rose by an order of magnitude and drivers were bracing their heads; going in corners in the anticipation of the centrifugal force.

The attention to detail in Formula 1 had never been more important. Even the location of petrol pumps on engines became a point for concern for designers as it caused unwanted turbulence in the air flow and to counter it, it was later moved towards the rear of the vehicle. Performance gains, irrespective of how infinitesimally small they were became main focus of teams.

Alan Jones won the championship in 1980 driving his Williams FW07B. Wright and Matthews (2001, pg 307) described the car as the 'definitive ground effect' car. The season of 1981 began with a ban on the skirts along the bottom of the sides of the vehicles. Rigid spoilers with at least 60mm clearance were introduced to counter the dangers of high cornering speeds due to the ground effect (Wright and Matthews, 2001; pg 309). Colin Chapman tried to work around this ban with his Lotus Type 88 by designing it with a double chassis but officials did not allow this and his car was banned from entering the competition. Nonetheless, 60 mm rule was never really followed by constructors during the race, as inspectors were unable to measure the difference, they lowered it anyway.

This season also saw the arrival of carbon fibre monocoques, first by Lotus and then by McLaren. While McLaren used moulded carbon fibre structures for its MP4/1, Lotus fabricated the carbon fibre chassis for Lotus 88 using existing techniques for aluminium monocoque structures (Smith, 2012). While carbon fibre monocoque was heavier than an aluminium monocoque, the advantage in torsional rigidity and driver safety outweigh the disadvantage offered by the increase in the weight of the car.

In 1982, Williams' Keke Rosberg won the title in a normally aspirated car. This was to be the last win for normally aspirated engines, as the turbocharged engines became a norm in 1983 season. Power output for these new turbocharged engines was higher than the normally aspirated engines. As a matter of fact, some engine manufacturers did not quote exact power figures of their engines, as the instrumentation on their test beds were insufficient to measure the power outputs of the turbocharged 1.5 litre engines. By 1983, engines had far exceeded the 1000 HP mark. BMW's 4- cylinder engine that brought victory to Nelson Piquet Jr in 1983 produced 1250 HP. Driving it around Monza, Italy in the qualifying for Italian Grand Prix, Benetton driver Gerhard Berger achieved a top speed of 351.220 km/h which was a new record and demonstrated the ability, and rapid evolution, of turbochargers in Formula 1. When Renault first introduced turbochargers, there were considerably issues with reliability and performance and sea level altitudes, and their utility was limited to tracks such as Kyalami track which is located at 1800 metres above sea level.

FIA changed the regulations in 1984 season by introducing pop-off valves to reduce the boost pressure coming from turbochargers to a maximum of 4 bars and then reducing it again to 2.5 bars. FIA also put a limit on the litres of fuel that could be used for every Gran Prix race at 150 litres. But this restriction was only put on turbocharged engines and the 3.5 litre normally aspirated engines were not subjected to fuel restrictions. Though due to the vast difference in power generated by turbocharged and non-turbocharged engines, normally aspirated engines were never really in any position to win the championship. Nikki Lauda won the title for McLaren in 1984 and his teammate, Alain Prost followed him in 1985, 1986.

1988 saw one of the most successful collaborations, in terms of points scored and race wins in a single season, in Formula 1 history. McLaren entered into a partnership with Honda. Honda was to supply engines for McLaren. Reduced boost pressure had forced the teams to move their attention from the pursuit of ever-higher HP figure. Power output of engines was now in the vicinity of 700 HP. Teams moved their attention to other aspects of the car. McLaren partnered up with Shell to improve the thermal efficiencies in the combustion chambers. With the limit of 150 litres of fuel every grand prix, Shell's unleaded fuel proved to be the distinguishing aspect of McLaren-Honda engine, providing superior power level, consumption and reduced friction losses. The results were decisive. Ayrton Senna and Alain Prost won 15 out of the 16 World Championship races for McLaren-Honda in 1988 season. The feat has never been equalled, let alone broken, since then. 1989 saw a ban on turbochargers and a return of 3.5 litre normally aspirated engines. Shell's unleaded fuel continued to produce results for McLaren.

*Table 15 Impact of individuals on organisational performance 1970 - 1990*

| **Discontinuities in the Network** | **Individuals** | **Impact on Organisational Performance** |
|---|---|---|
| Wind tunnel based car design, ground effect (1978) | Colin Chapman, Peter Wright (Lotus) | Lotus won the world championship in 1978 |
| Carbon fibre composite monocoque | John Barnard, Ron Dennis (McLaren) | McLaren went on to win five world championships between 1981 – 1990, carbon |

| | | |
|---|---|---|
| | | fibre composites were adopted by other teams. |

### 4.4. Evolving for 21st Century 1990-2010

This period is of importance for this study as the social network analysis is focused on this period. This period started with a change in regulation that banned turbochargers. One of the primary reason FIA banned turbochargers was to keep the costs down but two years after the ban, teams were spending 15-30% more on their 3.5 litre engines than what they were spending on their 6-cylinder 1.5 litre turbocharged engines (Atlas F1). The normally aspirated engines finally broke the 200 HP per 1000 CC of capacity mark and engine output reached 700 HP. Tyrrell team's constructors, Harvey Postlethwaite and Jean-Claude Migeot built the first 'high-nose' Formula 1 car. This innovation in aerodynamics has become indispensable to all modern Formula 1 cars.

McLaren won the championship in 1991. But this changed in 1992; the Williams-Renault partnership dominated that year. Their FW14B, equipped with active chassis (active suspension) adapting to the driving conditions and traction control preventing unwanted wheel spin in acceleration led to a world championship for Nigel Mansel. Discussing active suspension, Wright and Matthews (2001, pg 325) writes, " *the characteristics of a ground-effect race car are such that the development of active suspension was inevitable. The effect on the performance of the car also made it almost inevitable that active suspension would be banned.*"

In 1992, FIA introduced some changes to fuel regulations mandating that the fuel used in the cars only contains hydrocarbons and limited quantities of nitrogen and oxygen. A year later, FIA made it mandatory that the fuel used in cars must comply with European Union's fuel regulations for health and safety. These regulations brought an end to all the '*dark magic*' concoctions involving alcohol, nitrogen compounds and other HP-boosting additives. The engine tuning along with race-fuel was responsible for an incremental but an important increase in power during the race. New regulations required that teams had to submit a sample of race fuel to the authorities before the race and the fuel in the car on the race day should be identical in composition.

Ayrton Senna moved to Williams-Renault in 1994 and he looked poised for another title that year. But it was not to be and Senna, along with Austrian driver Roland Ratzenberger suffered fatal accidents on consecutive days at Imola in the qualifying session. This created an unprecedented backlash against Formula 1 in the media. Wright (2001) described it as '*existential crisis*.' FIA banned all the driving aids (e.g. active suspension and traction control) that year and in 1995, FIA also lowered the engine capacity to 3.0 litres. These regulation changes forced the teams to innovate at a rapid pace, because technologies such as traction control and active suspension had made driving Formula 1 car more manageable at high speeds (more than 250 km/h) and it was considerably more difficult for the drivers to control the car without any of these driving aids (Wright and Matthews, 2001).

In 1996, the William-Renault partnership succeeded and Damon Hill won the championship that year. Next few years saw Ferrari's Schumacher and Williams' Villeneuve closely fighting for the title with Villeneuve coming on the top. In 1998, Renault ended their partnership with Williams. Despite having won the championship just the year before, Williams could not win a single race in 1998. This goes on to demonstrate the critical nature of a competitive engine (and role of engine manufacturers) in grand prix winning car.

The FIA made more changes that year. Car width was reduced from 200 centimetres to 180 centimetres. Larger cockpits, from safety's point of view, were made mandatory. Rib-tread tyres, instead of the usual treadles slick tyres, were introduced to reduce the contact surface available to the car, and as a result reduce the cornering speed. FIA introduced four longitudinal grooves on the rear tyre and three on the front. In 1999, FIA stipulated an additional longitudinal groove on the front tyre. Later the same year, FIA banned the use of small additional wings on the side boxes. These regulations were introduced to make race cars more safe for the drivers. Furthermore, Formula 1 was now using fuel with greatly reduced sulphur content and aromatic additives that matched the European Standards.

2001 saw the reintroduction of traction control, which has been banned since 1994, to Formula 1. Schumacher again won the title comfortable with Ferrari winning the constructor's Championship. It's worth pointing out that at this juncture, Renault bought Benetton and the car maker begin taking part in Formula 1 under its own brand name. Ferrari again showed absolute dominance in the next season with Schumacher clinching the title with six races to go in the season and finishing with a podium place in every race. Ferrari's ability to tightly integrate its design and engine manufacturing resulted into a superior racing car. Ferrari won the 2003 and 2004 World Championships. Schumacher's role in bring engineering capabilities in form of Rory Byrne and Ross Brawn also contributed to Ferrari's performance.

FIA made head and neck support device (HANS) compulsory for all drivers in 2003. Though some drivers did voice complaint but FIA was serious about projecting an image of safe sport and to this day the HANS are mandatory. HANS was invented by Professor Robert Hubbard, at College of Engineering, Michigan University. An alliance of McLaren, Mercedes, and FIA developed the system further for adoption in Formula 1.

2005 season saw FIA introducing new 2.4 litre V8 engines to Formula 1 in place of the 3.0 litre V10 that have been powering the cars since mid 90s. In the 2008 season, none of the teams used traction control and McLaren won the title and Lewis Hamilton became the youngest driver ever to win the championship. It also marked the last year when the cars raced with grooved tyres. Slick tyres made their return in 2009 season. In 2009 season, Honda left the sports and the team was renamed as Brawn GP and went on to win the driver's world championship with Jenson Button.

2009 also saw some of the biggest changes made to Formula 1 in recent times. New Kinetic Energy Recovery Systems (KERS) were introduced to recover the energy from heat that is generated during braking. Slick tyres made a comeback to the Grand Prix racing track. Aerodynamic regulations were also altered. Front wings were made lower and wider with rear wings becoming higher and narrower. All the additional components such as winglets and turning vanes were completely removed and diffuser at the rear of the car was moved back and upwards. The idea behind these changes was to reduce the reliance on aerodynamic downforce for grip and increasing the mechanical grip. Next few years saw continued dominance of Red Bull with their exploitation of diffuser at the rear of the car to generate more down force and corner at higher speeds.

Table 16 Impact of individuals on organisational performance 1990 - 2010

| Discontinuities in the Network | Individuals | Impact on Organisational Performance |
|---|---|---|

| | | |
|---|---|---|
| Active suspension, automated driving aids (1991) | Patrick Head, Adrian Newey (Williams) | Williams won the next three world championships before FIA banned automated driving aids |
| Michael Schumacher joins Ferrari with Rory Byrne and Ross Brawn (1996) | Michael Schumacher, Rory Byrne, Ross Brawn, Jean Todt (Ferrari) | Ferrari won six world championships during Michael Schumacher's tenure (1996 – 2006) |

### 4.5. Why Formula 1?

The discussion in preceding sections describes how Formula 1 is composed of a global network of constructors, suppliers, and automotive manufacturers which are simultaneously competing and collaborating to overcome the technological and regulatory challenges within given time constraints. Formula 1 is essentially a prototype business as each year, teams must deliver a new product (i.e. car) and continuously evolve and introduce innovations over the season to maintain competitive advantage. Teams have to do this while simultaneously develop next year's product which, depending on regulations, could be considerably different in technical specifications than the present product and presents challenges associated with fast clockspeed industries.

The availability of performance metrics, that is grand prix results, make understanding the effect of this network on knowledge transfer process possible. Formula 1 is always at the cutting edge of automotive technology and how firms in Formula 1 manage pace of the technological development and regulatory challenges offer lessons for businesses such as information management systems, pharmaceutical industries, and aerospace manufacturers where firms form alliances with their competitors to tackle specific projects, expand their resource base, and overcome regulatory change.

There have been knowledge transfer studies focused on Formula 1 in the literature. Jenkins (2010) studied the technological discontinuity in Formula 1, Jenkins and Tallman (2015) researched the role of geography of knowledge sourcing in Formula 1 with a longitudinal single-case study focused on Ferrari. Aversa et al. (2015) research in Formula 1 identified business modes; a) of selling technology to competitors and b) developing and trading human resources with competitors as high-performance business models. Pinch et al. (2003) studied the evolution of clusters in Formula 1 and their (positive) effect on the dissemination of knowledge through the cluster. Jenkins and Floyd (2001) studied technological trajectories of three key technologies in Formula 1 at component, firm and system levels of analysis to understand relationships between technological transparency, co-evolution, and dominant design. Judde et al. (2013) studied the regulation change and its (positive) effect on the championship uncertainty and (no effect) long-term dominance.

While comprehensive in their scope, these studies have not explored the role played by individuals in knowledge transfer process and organisational performance in inter-organisational network. Formula 1 research in the literature is focused on exploring the business models and geographical location of organisations within the network, and there is a dearth of studies exploring the role of individual(s) or gatekeepers who influence and shape organisational performance. This study will fill that gap in the literature by using Formula 1 as a context for applying social network analysis.

### 4.6. Small World

The small world problem was first formulated by social psychologists in late 60s (Milgram, 1967; Travers and Milgram, 1967). The problem can be stated, in most simple terms as the probability of two people in the world knowing each other. Building up on that, one can expand the problem statement and argue that while two people might not know each other directly but they may have mutual acquaintances or intermediaries between them.

Watts and Strogatz (1998) came up with the analogous concept; small world networks. Watts and Strogatz (1998) defined small world networks as networks that are *highly clustered, like regular lattices, yet have small characteristic path lengths, like random graphs.* Social networks involving individuals or organisations are topologically different than physical networks, such as lattice arrangement in solid structures. This is not to say that social networks are like random graphs. Social networks have locales and clusters where if a node A in a social network is connected to node B, and node B is connected to node C, then there is a higher probability that node A and node C are acquainted, than two random nodes selected from a given population. This is not the case in a random graph where probability of any two nodes being connected is the same. Small world networks model social networks, and consist of a network topology like a regular lattice, and possessing average node to node distance comparable to that of random graphs (Adamic et. Al., 2003; Albert and Barabasi., 1999; Newman, 2001; Kleinberg, 2000). The technological overview of the Formula 1 network shows small world properties. This has implications for how nodes behave within the network.

Uzzi et al. (2007) posit that small world as a research tool allows for an *unusually parsimonious set of explanations for many different systems as well as the behaviour of the nodes embedded within them (Uzzi et al., 2007 pg. 12.*) The small world phenomena is important in studying real life networks as it establishes the fact that even in large networks with thousands of nodes, there is a relatively short path connecting any given pair of nodes (Albert and Barabasi, 1999). Telesford et al. (2011) highlight the *unique ability* of small world networks to simultaneously have highly clustered regions with strong connection within the community of nodes and exhibit shared (or distrusted) processing through the network.

Researchers have studied small world phenomena with a focus on concept of small distances or path length between any two nodes in a network (Conwan and Jonard, 2004; Newman, 2001). A small world network facilitates innovation by creating '*short cuts'* in a large network (Cowan and Jonard, 2004). Newman (2001) cites examples of scientific community with a network structure of a small world. In such a network it should be relatively easier for one actor working on a new problem to find an expert on the subject matter.

Small world phenomena have been observed in many real life contexts. Nervous systems, collaborations in scientific publishing, investment banking, and film collaborations. (Newman, 2001; Newman, 2003; Schnettler, 2009). Some scholars (Buchana, 2002; Telesford, 2011) argues that small world networks are ubiquitous though there are many examples of real life networks that are not small world. Goyal et al. (2006) found that authorship network of economists (1980 – 1999) was a small world network, Moody (2004) found that not to be true for sociology authorship network (1963 – 1999). Schnettler (2009) and Newman (2003) comment on common occurrence small world phenomena and suggest that small world network conditions are not demanding. Relatively less demanding conditions for existence of small world networks explain why they appear *ubiquitous* (Telesford, 2011).

Robins et al. (2005) found another potentially reason for ubiquity of small world networks. They found in their simulations that even node centric processes can lead to small world networks, especially in cases where nodes has more than one connection. Scholars have also found that node centric processes and attributes affect the whole network and there is a relationship between node level and network level metrics (Baum et al., 2003; Corrado and Zollo, 2006; Guimera et al., 2005). Mishra et al. (2017) highlight the nature of gatekeepers. There gatekeepers can span boundaries of different clusters in the network and may lead to formation of small worlds. This may lead to creation of more gatekeepers who can encourage more information and knowledge flow and facilitate network growth without losing connectivity.

### 4.7. Innovation and Small World Networks

One of the first studies to explore the relationship between small world networks and innovation was focused on examining technology alliance in chemicals and electronic industries (Verspagen and Duysters, 2004). Verspagen and Duysters (2004) described the network as highly clustered and having low average path length between any two nodes. Balconi et al. (2004) also identified similar characteristics in their study of Italian inventors. They found that the collaboration networks in the electrical and chemical industries are more connected than other networks. Despite the differences in their respective methodology, Verspagen and Duysters (2004) used European MERIT CATI dataset and Balconi et al. (2004) used patent data to establish connections, their finding are similar. This implies that certain traits within certain industries are more conducive for small world networks.

Cowan et al. (2007) did a simulation based study where they showed how small worlds form within innovation networks when embeddedness is a driver for alliance formation. This embeddedness leads to cluster formation which is critical for formation of small world networks. Gay and Dousset (2005) did a study on biotechnology sector (specifically antibody industry) and found that the industry network had small world characteristics. They also remarked on how 72% antibody industry network alliances involved some form of research and development agreement. In this particular study, robustness of small world structures within the main component of the network point to relationship between aspects of technology and innovation process. Cowan et al. (2007) simulation study supports this argument that there is a link between industry specific innovation processes and small world networks. Uzzi (1997) has identified embeddedness as arising from repeated interactions between firms based on trust and shared understanding. In case of small world networks, this embeddedness allows for inter cluster connections.

Although these studies identify small world phenomena's occurrence in alliances centred on innovation, they fail to provide evidence for a relationship between small world networks and *innovation outcomes* (Steen et al., 2011). The common occurrence of small world network in different industries and systems imply that small world network properties have little influence on innovation. Uzzi and Spiro (2005) study challenges this assumption and demonstrates the influence of small world on innovation. The study is set in Broadway, and analyses the collaborations data between 1945 and 1989. Using the data on teams of artists, Uzzi and Spiro created a network of musicians working on different musicals in different periods. They found that small world indicator, called small world coefficient and performance is an inverted U shape. This implies that possibility of musical being successful, at the peak value of small world indicator, is three times higher than where the small indicator is at its lowest value.

Granovetter (1973) conclusions about redundant information in networks and Burt's (2004) observations about connections between disparate groups giving rise to innovation complement Uzzi and Spiro's findings. A network with a very large Q implies a densely connected network where there is no diversity of knowledge or mechanism to introduce novel knowledge through disparate cluster of nodes or peripheral nodes.

Small world networks have implications for innovation and knowledge transfer. Small world networks are structured such as to encourage knowledge flows within the network. The clusters within the network involve nodes in cohesive communities exchanging information, and relatively short path lengths ensure that novel knowledge can be introduced via individual (s) from a different cluster. This face to face interaction is critical for tacit knowledge which is embedded in individual and difficult to transfer in the context of Formula 1 (Argote and Ingram, 2000; Cummings and Teng, 2003; Squire et al., 2009, Aversa et al., 2017)

The small world nature of Formula 1 network will imply unusually large information flowing within the network through links between nodes (gatekeepers) who have either worked together in past or connected to each other through another actor (Uzzi and Spiro, 2015; Mishra et al., 2017). The small world of Formula 1 means that novel knowledge is introduced in the network via these gatekeepers and then dispersed through the whole network and constituent clusters.

Small world networks also have implications for state of innovation (Uzzi and Spiro, 2005; Burt, 2004; Steen et al., 2011). A moderately high small world coefficient will imply novel knowledge flow between peripheral nodes and central clusters. This type of knowledge is critical for innovation.

As discussed in previous sections, Formula 1 offers an ideal context for this study. A technological overview of the Formula 1 network, with its high information flow and technological innovation, highlights the small world properties of the network. The next chapter shows the importance of individuals with high tacit knowledge content on the organisational performance in the small world network of Formula 1. The quantitative assessment of the Formula 1 network, in chapter 6, confirms and extends the qualitative findings.

# Chapter 5: Interviews and Case Studies: Qualitative Analysis

This chapter is divided in two sections. The first section is focused on interviews and analysis and the second chapter is focused on case study analysis.

## 5.1 Interviews

Interview analysis was done based on the framework developed in chapter 2 (figure 3, page 18). The goal of analysis was to verify the veracity of the framework and explore the existing academic consensus on nature of tacit knowledge transfer in Formula 1. To this end, the following table lists labels developed from the framework and wider literature for analysing interviews.

*Table 17 Labels for analysing interviews*

| **Labels** | |
|---|---|
| <u>Motivation behind Strategic Alliances</u><br>This construct focuses on why organisations get into alliances in inter-organisational networks. | Smith et al., 2007; Stauffer, 1999; McEvily et al., 2004; Kogut, 1988; Inkpen and Tsang, 2005; Grant and Baden-Fuller, 2004 |
| <u>Process facilitating knowledge transfer</u><br>This construct identifies key processes in alliances and the wider inter-organisational network that support knowledge transfer. | Szulanski, 1996; Chen 2004; Cavusgil et al., 2003; Song et al., 2003; Appleyard 1996; Aversa et al., 2015; Baughnet al., 1997; Choi and Lee 1997; Dodgson 1996; Mowery et al., 1996 |
| <u>Factor affecting said processes</u><br>This construct explores the factors that affect the process identified as facilitating knowledge transfer | Rebnitsch and Ferretti, 1995; Ahuja, 2000; Song et al., 2014; Garud and Nayyar, 1994; Simonnin, 1999; Cummings and Teng, 2003; Schulze et al., 2014 |
| <u>Industry variables and their role (Competition, Technology, Evolution)</u><br>This construct describes how various aspects of industry affect knowledge transfer process in inter-organisational networks. | Ahuja, 2000; Pinch et al., 2003; Aversa et al., 2015; Yoshino and Rangan, 1995; Gomes-Casseres, 2006; Pinch et al., 2003; Rond and Marjanovic, 2006; Jenkins and Tallman, 2015; Ahuja et al., 2008; Dyer and Singh, 1998. |
| <u>Nature of knowledge transfer (Degree of Tacitness)</u><br>This construct explores how the degree of tacitness affects the knowledge transfer process. | Chen, 2004; Cummings and Teng, 2003; Reagans and McEvily, 2003; Zhao and Lavin, 2012; Argote and Ingram, 2000; Lam 1997; Nelso and Winter, 1992; Polanyi, 1964, 1967; Battistella et al., 2016 |

| | |
|---|---|
| Dimensions of knowledge transfer (prior alliances, core competencies, absorptive capacity, trust)<br>This construct explores how various dimensions of knowledge transfer (as identified in the literature) affect the process. | Lyles, 1998; Lyles and Gundegran, 2006<br>Quintas et al., 1998; Ahuja, 2000<br>Tsai, 2001; Lichtenthaler and Lichtenthaler, 2010 |
| Critical factors for success of knowledge transfer process in alliances<br>This construct identifies which factors are critical for successful knowledge transfer in alliances. | Inkpen and Tsang, 2005; Kogut, 1988, Adams et al., 1998; Grand and Baden-Fuller; 2004; Hardy et al., 2003; Appleyard 1996; Baughn, et al., 1997; Choi and Lee, 1997; Dodgson, 1996; Mowery et al.,1996; Garuda and Nayar, 1994; Cummings and Teng, 2003. |

### *Motivation Behind Strategic Alliances*

Interviewee 1 suggests that key aspect behind formation of strategic alliances in Formula 1 is to win races, and the Formula 1 car is an alliance. The interviewee goes on to highlight the case of Red Bull Racing team and Renault Sports, their engine supplier and the series of problems faced by their alliance because of underperforming Renault engine. Alliance formation is also motivated by a search of knowledge they do not have and to encourage knowledge flow between partners.

Interviewee 2 argued that knowledge transfer is indeed a driving force behind alliance formation. Interviewee 3 suggested that it is difficult to ascertain exact motivation for alliance formation in Formula 1 considering that there is a history of organisations investing considerable resources, monetary and human, only to come short and get beaten by smaller British teams with miniscule operating budgets. Interviewee 3 also highlighted how in recent years one team, Mercedes AMG, has been head and shoulder above everyone and it can be attributed to their different inter-organisational structure (compared to teams such as Ferrari and Lotus) and investment in research.

### *Process Facilitating Knowledge Transfer in Alliances*

Interviewee 1 suggests that it is the myriad of connections between people in collaborating organisations that facilitate knowledge transfer and cites the example of current Formula 1 tyre supplier, Pirelli which has engineers working with every team. Interviewee 2 suggests that prior alliances and co-location (geographical proximity) plays a key role in facilitating knowledge transfer and goes on to highlight how Hass F1, an US based Formula 1 constructor, opened a technical centre in the motorsport valley in Britain. This, the interviewee argues, explains why teams like HRT could not perform well. Synergetic and complementary alliances are essential for knowledge transfer.

Interviewee 3 highlighted research collaboration, funding, and lack of capability as key factors facilitating knowledge transfer in alliances. Interviewee 3 also argued that less regulation can facilitate Formula 1 teams to get into alliances for knowledge transfer.

### *Factors Affecting said Processes*

Interview 1 argues that clusters are an important factor that affects the processes facilitating knowledge transfer. Clusters encourage knowledge sharing within the cluster boundary but also isolate the members from accessing those outside of clusters, and this is known as paradox of clusters and is key factor that affects the process of knowledge transfer. Interviewee 1 also argues that since Formula 1 teams rely on tacit knowledge within individuals than on intellectual property, people to people contact and the accompanying network is essential for knowledge transfer.

Interviewee 2 suggests that it is lack of capability which is behind processes that facilitate knowledge transfer in alliances. Formula 1 is a prototypical product business and as such lacks economies of scales and by entering in alliances and knowledge transfer, teams can access knowledge they lack and make cost savings. Interviewee 3 argued that it is the decline of Formula 1 which is encouraging teams to get into alliances and facilitate knowledge transfer to access novel knowledge and gain competitive advantage.

### *Industry Variables and their Role*

Interviewee 1 argues that beyond competition, technology, and pace of evolution, regulation is the key industry variable that affects knowledge transfer in alliances in Formula 1. Regulations can change the balance of competition and the direction of evolution of technology. Regulatory interventions also cause disruption, as observed in case of introduction of turbocharges by Renault in 1970s and kinetic energy recovery system in 2010s.

Interviewee 2 argued that innovation also plays a role in affecting knowledge transfer process in alliances in Formula 1. The interviewee goes on to highlight how Mercedes had refused to form an alliance with Red Bull Racing for the 2016 season because of Red Bull's ability to exploit their expertise in aerodynamics and potentially perform better than the works teams, that is Mercedes. Interviewee 3 argues that from perspective of the wider automotive industry, Formula 1 technology is not suitable for road cars and as such does not require substantial investment or participation on their part.

### *Degree of tacitness*

Interviewee 1 suggests that various partners absorb tacit knowledge by working closely with Formula 1 teams and apply it to their other partners within Formula 1, and in some cases, in their road car business. Interviewee 2 identifies tacit knowledge as very important since it is difficult to imitate and it copes with Formula 1 teams' need for secrecy. Formula 1 teams do not file patents, and tacit knowledge drives innovation within Formula 1 teams.

Interviewee 2 goes on to argue that quickest way to innovate is to hire people from companies you are trying to imitate. Tacit knowledge is also a driving factor behind interfirm mobility between teams. Interviewee 3 suggests that tacit knowledge enhances organisational impact and ability of teams to do system integration. The interviewee also highlights Lotus teams culture and approach to racing which was inherently tacit and led to them become one of the most successful teams in Formula 1 history.

### *Dimensions of Knowledge Transfer*

Interviewee 1 argues that a history of prior alliances can only benefit alliance partners if they can deliver technology that is appropriate and goes on to cite case of Ross Brawn at Mercedes and his role in encouraging development of hybrid engine technology and Red Bull's expertise in aerodynamics. The interviewee also suggests that there is little if any transfer from Formual 1 to automotive industry. About core competencies, interviewee 1 suggests that Formula 1 team share only those technologies that they either view as obsolete or not threatening to their own prospects in races.

Interviewee 2 suggests that while prior alliances can play a constructive role in knowledge transfer, but they can also be a hindrance. In terms of protecting their core competencies, interviewee 2 argues, teams do not share the source of their key competitive advantage, as was the case when Mercedes refused to supply Red Bull Racing with the power units. It was believed that with their expertise in aerodynamics and Mercedes power unit, Red Bull car would have been a better performing package than Mercedes'. Interviewee 2 also highlights how Mercedes does not deliver engine updates to its other alliance partners as quickly as to its own factory team. Absorptive capacity is important to knowledge transfer as collaboration is drive by a desire to learn which is different than their domain expertise.

Interviewee 3 highlights the importance of prior alliances, cites the case of BRM, a British engine manufacturer and Lotus Formula 1 team partnership in 1960s. In this case, BRM withdrew from the sport because of regulation change, and it was the relationship between BRM technical director, Rudd and Lotus team principal, Chapman, which led to Rudd moving to Lotus and few seasons later, wining world championship. The interviewee also highlights merger as another key variable that allows teams to absorb knowledge and core competencies of their alliance partners and facilitates knowledge transfer.

### *Other Factors affecting Knowledge Transfer*

Interviewee 1 suggests that primary factor motivating knowledge transfer is ability to access novel knowledge. The interviewee also highlights alignment, complementaries, and competencies as external factors influencing knowledge transfer. Interviewee 2 highlights integrative capability as another factor affecting the process.

Interviewee 3 argues that regulations are restrictive and negatively affect knowledge transfer by setting tight boundaries and allowing for minimum manoeuvrability for engineers and researchers in Formula 1.

### *Critical Factors for Success of Knowledge Transfer Process in Alliances*

Interview 1 highlights system integration as the critical factor for success of knowledge transfer in alliances in Formula 1. A Formula 1 team's ability to integrate different and varied technologies into the race car is key for knowledge transfer success. Formula 1 teams have a long history of integrating different and novel technologies into race cars, such as 3-D printing. Cultural alignment also plays an important role in success of knowledge transfer process, as can be observed in the way Mercedes AMG racing team has organised itself as a distinct company from the parent organisation, Daimler AG.

Interviewee 2 suggests financial resources, technical expertise, and ways of doing things are critical for knowledge transfer success. Formula 1 teams are good at exploiting their partners' knowledge and learn how to work with a particular technology. Another factor affecting the success of knowledge transfer is the type of alliance, if it is customer and component producer alliance, then it has more chances of being successful. Interviewee 2 also highlights how it is difficult to measure success of knowledge transfer, and how it is idiosyncratic to the task. Interviewee 3 highlights research and development as the critical factor behind the success of knowledge transfer in alliances in Formula 1.

### *Directionality and other Aspects*

Interview 1 argues that directionality is important but not the critical factor for knowledge transfer success. Other aspects such as knowledge, people, relations, and organisations coming together play a role in success of knowledge transfer. Knowledge transfer process is also driven by constant development. In terms of transfer of technology between Formula 1 and automotive industry, the interviewee 1 suggest that while technological overlaps do exist, compatibility of capabilities more analogues to aerospace and defence industries. Although in past, alliance partners have tried rotating their engineers through Formula 1 for capability development, as Honda did with their alliance partner McLaren in late 1980s. Formula 1, as an industry, has more in common with aerospace and Silicon Valley based companies like Apple, Google, and Tesla than automotive industry.

Interviewee 2 highlights that Formula 1 offers a test bed for technology where companies can push the technological boundaries of their products and highlights the long standing electronic component manufacturer, Magneti Marelli, a partner of Ferrari, as using Formula 1 to test specific technological components. Interviewee 2 describes Formula 1 as the Big Brother of an R&D lab. Big Brother is a voyeuristic reality television program.
Interviewee 2 argues that Formula 1 has a responsibility to build technologies for automotive industry and both industries share plenty of application and opportunities for developing technologies. Practices, or way of doing things, in Formula 1 offer universal lessons for all industries.

Interviewee 3 suggests that there is little bidirectional transfer between Formula 1 and the automotive industry since early 1980s as the engine and chassis technologies of Formula 1 cars and road cars have developed in different directions. The interviewee also highlights how it is easier to design a Formula 1 engine than a road car engine and that current Formula 1 engine is a dead-end technology.

The following table lists the interview findings and corresponding tacit knowledge transfer variables identified in the framework.

Table 18 Interview findings

| **Variable for Tacit Knowledge Transfer** | **Interview Findings** |
|---|---|
| Degree of tacitness, trust, and technology | Certain individuals are key exponents of tacit knowledge. |
| Degree of tacitness, prior alliances, proximity to core competencies | Movement of these individuals is linked with improved organisational performance. |
| Prior alliances, proximity to core competencies, technology, evolution of the industry, and competition | Formula 1 cars are prototypes that are essentially an alliance between chassis constructor, engine manufacturer, and various technical partners. |
| Degree of tacitness, technology, competition, evolution of the industry, motivation behind strategic alliances, and trust | Motivation behind this *alliance* is accessing the knowledge that can help the team win races. Teams are looking for knowledge within the inter-organisational network for competitive advantage. |
| Degree of tacitness, trust, and technology | Most innovations and technologies developed in Formula 1 are not patented and teams rely on individuals and the knowledge (of technologies and way of doing things) residing within them for improvement and performance gains. |
| Competition, technology, and proximity to core competencies | If a team does not have access to such knowledge, it will rely on movement of individuals from other successful teams and their know-how to access the said knowledge. |
| Degree of tacitness, trust, and competition. | Team’s ability to integrate individuals and technologies is critical for its success. Teams are essentially system integrators for different technologies. |

| | |
|---|---|
| Competition, and evolution of the industry | Regulation changes play a key part in facilitating knowledge transfer through technological discontinuities. |

### 5.1.1 Interview Findings

Interviewees emphasised the unique nature of Formula 1 cars, and termed them as an *alliance.* The prime objective of this alliance is to *win races.* This alliance is primarily formed to acquire the knowledge, resources, and capability that a team lacks. These alliances are driven by past collaboration and geographical colocation. Geographical co-location is a particularly important aspect of success in Formula 1 as most of the teams and suppliers are located in what is known as motorsport valley in United Kingdom and motorsport valley in Italy. Knowledge flow itself is bidirectional and is driven by its value for application.

Formula 1 cars are prototypes and make achieving economies of scales difficult. Getting into an alliance not only facilitates cost saving but also provides access to otherwise difficult to reach knowledge. Alliance and knowledge sharing are also dependent on the partner's ability to innovate. Companies do not get into alliance if their partner can "*out-innovate"* them in performance

The process of knowledge transfer manifests in the connections between people in collaborating organisations. This network of organisation relies on movement of personals to gain knowledge, capabilities, and processes and as a result Formula 1 teams have a high interfirm mobility. Knowledge moves in clusters and is dependent on people-to-people contact. This network of people is critical as Formula 1 technological gains are never patented or seen as intellectual property that needs to be protected and rely on their personnel to propagate knowledge through the organisation. This makes members of world championship winning teams attractive for other teams and not necessarily because they can potentially bring same technologies but more so because they bring their know-how that is tacit knowledge. Hiring personnel from successful teams is also considered a way to encourage innovation.

The network of people driving knowledge sharing is contextualised by the competition and technological evolution as well as regulation. Regulation change can alter the balance of competition and change the trajectory of technological evolution. Regulatory changes can also cause disruption. The nature of knowledge is critical for transfer process. Learning the processes and way of doing things is perhaps more important that the technologies. This type of tacit transfer is critical for partners in alliances. Lack of capability and monetary resources also affect the process of knowledge transfer. Research collaboration is also a motivating factor behind knowledge exchange between alliance partners'. Interviewee three presented the view that less regulation can facilitate more collaboration, knowledge exchange, and innovation.

A history of past alliances can have a positive effect on the transfer process if alliance partner can deliver technology appropriate for the team. Prior alliances can also be a hindrance as well. Teams often refuse to collaborate where their core competencies can complement partner's core competencies resulting in partner having a better car on the track. The absorptive capacity of a potential alliance partner is critical for knowledge transfer success and often teams form alliances to access the knowledge that the team lacks. The ability to integrate different technologies, knowledge, and people is at the core of a team's success. Financial resources play a key role in success or failure of knowledge transfer process as well as ability of personal in the team. Partners are protective of their core competencies and only share technologies that they have already incorporated in their cars and in process of developing and improving it

The nature of Formula 1 means that alliances are primarily driven by 'knowledge', knowledge that can help a team win races. Other external factors such as corporate alignment and complementary competencies do play a role but gaining knowledge and technologies remain the prime motivator for these alliances. The nature of knowledge transfer is determined, and driven, by the organisational culture and the ability of teams to integrate different personal and technologies. In terms of the ability of alliance partners, the ability to absorb and incorporate knowledge depends on cultural compatibility and prior alliances. Regulations negatively affect this process by restricting the ability of teams to apply all their technical know-how.

A critical factor for success of knowledge transfer in alliances is research and development. Teams investing in research are not only able to innovate but also gain from knowledge of alliance partners. Formula 1 cars are essentially an alliance. These cars are result of integration of the technological know-how of the alliance partners thus system integration is critical for success of the alliances. How external capabilities, financial resources, and personal are integrated into the process of building a car influences success or failure of the team.

Formula 1 is essentially a prototype development business and is dependent on factors such as knowledge, people, and relationships coming together and having compatible capabilities. Formula 1, as a business, shares more similarities with computer manufacturers like Apple or Google, video game developers, and aerospace and defence manufacturers than automotive companies.

Performance of alliances in Formula 1 can only be judged within their unique context and intra-industry alliance knowledge transfer success is judged on different parameters than the external knowledge transfer. Formula 1 teams do offer certain universal lessons in terms of "practices" and "how to do things". Formula 1 also offers a unique research and development laboratory for automotive and other manufacturers to test their products and technologies.

Interviews also highlight that it is difficult to decipher the exact motivations behind strategic alliances between automotive manufacturers and Formula 1 constructors. Participation in Formula 1 requires a substantial investment without any guarantee of returns, and there are concerns with damage to the brand. Automotive manufacturers do not want to make such an investment and lose against smaller teams with fewer resources.

In terms of knowledge transfer from Formula 1 to road cars, the technology being used and developed in Formula 1 is not suitable for road cars. Cross over between racing and road car technology is almost non-existent. Interviewees argued that there was an alignment between road and Formula 1 technologies in pre 1990s era and since then, Formula 1 cars have been following a different technology trajectory to that of road cars.

In terms of directionality, the process of building a road car engine is much more challenging than that of a Formula 1 (or an Indy Car) engine. There are certain venues for transfer of expertise, practices, and way of doing thing, but beyond that there is not much scope for technological transfer from Formula 1 to road cars.

## 5.2 Case Studies

The following case studies explore the interview findings through specific cases. The qualitative analysis provides a comprehensive and contextual exploration of interview findings. There are three cases, Renault RS01: the first grand prix car to use turbocharges, Ford Cosworth DFV: the most successful grand prix engine in the history of the sport, and tenure of Ross Brawn at Ferrari between 1996 and 2006. The following table highlights reasons for selection of specific cases,

*Table 19 Case Studies*

| Cases | Interview findings and Framework of Tacit Knowledge Transfer |
|---|---|
| Renault RS01 | Renault RS01 was the first grand prix car to use turbo charged engine. This engine was based on the LeMans engine and involved close cooperation between LeMan engine designer and the Formula 1 engine designer and driver. It facilitates an examination of importance of individuals, tacit knowledge, impact of individuals on the organisational performance system integration capabilities, and role of regulations in motivating innovation. |
| Ford Cosworth DFV | The DFV engine remains the most successful grand prix engine in the history of the sport. The collaboration between Lotus and Cosworth allows for an examination of individuals, their impact on the organisational performance, role of prior alliance, proximity to core competencies, trust, role of regulations. |
| Ferrari: Brawn Era | Ferrari had its most successful ten year period with Brawn, Byrne, Schumacher, and Todt in the team between 1996 and 2006. This case allows for exploration of role of individuals, their impact on organisational performance, trust, prior alliances, competition, evolution of industry, and regulations. |

### *5.2.1 Renault RS01: The Yellow Teapot*

FIA rules have permitted the use of 3.0 litre normally aspirated engines or 1.5 litre forced induction engines in Formula 1 cars since 1966. Despite this, most constructors stayed away from using turbocharged engines mainly due to the issue of ‘power lag’ and ‘fair equivalency’. During late 1970s, Ford Cosworth DFV engines dominated Formula 1. Though constructors like Ferrari were focusing on developing their own flat-12 engine, almost all other constructors were using Ford’s DFV engine.  Renault was the first constructor in more than two decades to introduce a forced-induction engine in 1977. The engine in RS01 was based on the 2.0 litre V6 engine used by Renault in LeMans Sports Racing car. RS01 was designed by Andre de

Cortanze and Jean-Pierre Jabouille, who also drove the car in grands prix. RS01 made its first appearance on Grand Prix circuit in 1977 at British Grand Prix in Silverstone. Renault entered Formula 1 with a turbocharged engine to promote its range of turbocharged road going cars (Wright and Matthews, 2001, pg. 208).

Turbocharging was originally developed in the United States during the World War II for aircraft engines and was applied to road cars only in 1960s. Turbochargers work by taking the residual energy in the exhaust gases and expanding it through a turbine to drive the intake compressor, and by doing so, expand the piston engine output to almost double its capacity (theoretically).

Renault's involvement in motor sports started with the founding of a new factory at Viry-Châtillon on 6 February 1969. Initially Renault focused on a new 2-litre V6 engine for competing in the European 2-litre sportscar series and subsequently moved to the FIA World Sportscar Championship with a turbocharged variant. Renault Sport was founded in 1976 and started working on a single-seater programme with the V6 engine in European F2. In sportscars the turbocharged Renaults proved to be successful and in 1978, Renault won the Le Mans and subsequently focused on being competitive in Formula 1. The turbocharged engine was derived from CH series of engines designed by Francois Castaing, and the Formula 1 variant for RS01 was developed by Bernard Dudot.

Renault struggled with their car for first two years, primarily due to lack of reliability of the turbocharger. Turbocharged engines presented problems, such as driveability due to turbo lag, need for electronic fuel and ignition management for precise control of lean mixtures without detonation, and special fuel (Wright and Matthews, 2001). Ken Tyrell dubbed Renault RS01 as 'the yellow teapot' due to its frequent breakdowns and engine emitting steam (or smoke) while parked at the side of the track. In the South African Grand Prix at Kyalami, Renault was the fastest car in the qualification, first for a turbocharged cars. The high altitude of Kyalami created problems for Ferrari's flat 12 and Cosworth's DFV but saw Renault's turbocharged engine running at its maximum capacity.

By 1979, Renault's car started to show promise. François Castaing, Michel Tétu and Marcel Hubert developed the new ground effect chassis, RS10 for the season and at Monaco Grand Prix, Renault fitted its turbo-charged engine to the new chassis. RS10 started delivering results with the very next grand prix in Dijon, France. It was the first time since 1906 that a French driver won the French Grand Prix in a French car with a French engine using tyres from a French manufacturer (Michellin) and a French fuel supplier. Next few years saw Renault making steady progress in drivers and constructors championship. Renault never won the world championship with their turbocharged engines but the innovation that they introduced in the Formula 1 car engine technology is analogous to disruption (Christensen, 2006). RS10 had higher boost pressure and an inter cooled turbocharged engine that produced more power than the normally aspirated engine with twice the capacity (Wright and Matthews, 2001). Turbo-lag presented problems for the Renault cars in the corners but in the straight line, normally aspirated engines were no match for the Renault. Other constructors noticed this development and started working on the turbocharged engines that could produce more power than the existing normally aspirated engines. This is an example of Formula 1 teams learning from their competitors. This pursuit of ever-higher power output could only be supported by the automotive manufactures, and turbocharging brought back the support of the automotive manufacturers to Formula 1 (Wright and Matthews, 2001, pg. 38). The automotive manufacturers, on their part, were aware of the potential that turbocharging offered for road cars in terms of cheaper manufacturing costs, smaller capacity engines, fuel efficiency, and emissions, and Formula 1 provided a laboratory for the manufacturers to test out the technology.

Early years of 80s saw BMW, Porsche, Honda, Ferrari, Ford Cosworth, and Alfa Romeo introducing turbocharged engines, with the BMW turbo engine becoming the first turbocharged engine to win the world championship in 1981 followed by TAG Porsche in 1982. With the help of fuel chemists, the power output of the turbo engines kept on climbing. BMW even produced a 1200 HP four-cylinder engine. Most manufacturers' engines were producing about 800 HP per litre. The pressure of air; being fed by compressor in these turbocharged engines was 4 bar and with the high-density fuel, they did not last more than few laps.

Wrigh and Matthews (2001, pg. 208) argue that this intensive development of turbochargers in Formula 1 'undoubtedly' benefited the road cars. The development of turbochargers in Formula 1 played a constructive role in the development of electronic fuel injection and computer controlled ignition. Turbocharged engines are difficult to fuel across the wide range of rpm, throttle and boost settings, making electronic fuel injection and computer controlled ignition and fuelling essential for extracting full potential of these engines. Turbocharged engines were generating four times the power for a given cylinder size compared to a normally aspirated engine and this presented heating issues. To counter this, specialist fuel blends were developed to provide internal cooling and high-energy release.

This series of changes is a common occurrence in Formula 1, one innovation leading to another. It was the introduction of turbocharging by Renault that led to electronic fuel injection, controlled ignition, and specialist fuel blends in the Formula 1. This highlights how knowledge flows across the organisational boundary in a network. Once Renault had introduced turbochargers, and demonstrated its capability, other teams followed and found themselves developing technologies such as controlled ignition and electronic fuel injection to fully exploit turbochargers.

Renault was able to employ this technology effectively because it had this set of knowledge in past projects (Szulanski, 2000) and they had used the turbocharged engines in the past projects, including their Le Marns sports racing car and had entered the Formula 1 with intentions to promote their road going turbo-charged cars. Renault was also an expert in the knowledge field (Szulanski, 2000) as one of the biggest French Automotive manufacturers and was a pioneer in developing turbocharged engines for Formula 1 and road cars in Europe. In addition to their expertise, Renault was able to target outcome of specific action (Suzlanski, 1996) with their continuous development of inter-cooled engines and high boost pressure.

Renault established the performance incentives of switching to turbocharged engines and entered the Formula 1 with the intention of promoting their road going turbocharged cars, but in doing so their innovation in the engine technology revolutionised the Formula 1 and led to the development of other technologies such as pneumatic valve, electronically controlled fuel management, and electric ignition. This is significant in the context of monopoly of Ford Cosworth DFV engines in Formula 1. Renault identified that to break the monopoly, Formula 1 needed a different approach to engine design. Ferrari was employing the same approach with their development of flat-12 naturally aspirated engine. Renault identified the gap in the Formula 1's knowledge base, an important feature for any knowledge transfer process (Carlile and Rebentisch, 2003). FIA regulations allowed the use of 1.5 litre forced induction engines since 1966 car, constructors ignored them due to false equivalency but Renault realised the potential of the technology and with their innovations, made it viable.

An important feature of any knowledge transfer process is the source firm's ability to abstract the knowledge from the day-to-day context (Sobek et al., 1998) and provide all the necessary background information to the recipient (Carlile and Rebentisch, 2003). Renault, followed by BMW, Porsche, Honda, and other manufacturers' experience of turbocharged engines in grand prix helped them in developing a more comprehensive technology for their road cars (Wright and Matthews, 2001). Engine manufacturers demonstrated that their experience of turbocharged engines in the context of Formula 1 can help with the implementation of the same technology in production cars.

This needs to be seen in the context two different units of analysis, first is the firm itself where manufacturers like Renault and BMW's development of turbocharged engines in Formula 1 led to vertical knowledge transfer (Brooks, 1968) to their road going cars. The second unit of analysis is the industry itself where one observes the intensive development of turbochargers in Formula 1 providing benefits for the production cars (Wright and Matthews, 2001). In the case of auto manufacturers, vertical knowledge transfer takes place with sharing of all the relevant information and data. In case of constructor and engine suppliers, such as BMW and Brabham, the car and turbocharged engine is developed in parallel.

Squire et. al (2009) highlight the importance of source firm engaging in communication and sustained dialogue with the recipient firm to facilitate the transfer of tacit knowledge. Automotive manufacturers taking part as constructors and making their own engines and chassis had more success in transferring the knowledge. Constructors with automotive manufacturers acting as engine suppliers perhaps had more difficulty in transferring the tacit knowledge but the concurrent development of car and engine with continuous interaction could have facilitated tacit knowledge transfer. Renault got involved in sports racing, and subsequently in Formula 1, to promote their production cars with turbo-charged engine. Renault engineers who worked in the technologically demanding and sophisticated field of Grands Prix went on to work on the production cars and carried their tacit knowledge with them.

Szulanski (1996) highlight the role of the recipient firm in knowledge transfer process and its ability to take appropriate actions to prepare its staff for absorbing the knowledge. This was the case with Renault RS01 and RS10. Renault were producing their own turbocharged engine and ground effect chassis, Renault engineers knew the technology and the development curve and could better absorb the knowledge from their Formula 1 operations to production car operations. For other constructors and automotive manufacturers, collaboration on turbocharged engines led to specialist in the industry who developed facilities and personnel to engineer and refine these engines (Wright and Matthews, 2001). Mietzel (2007) highlight the importance of a firm's ability to convey the set of knowledge gained to others for the success of knowledge transfer (cited by Schulze et al., 2014). This construct perhaps best manifests itself in case of vertically integrated constructors such as Renault where they used their expertise on turbochargers in Formula 1 to develop and refine their road going cars

Prior alliances play an important role in successful collaborations (Fosfuri and Tribo, 2008). In these terms, constructors in Formula 1 had always been involved with automotive manufacturers, and with the success of Ford Cosworth DFV engine, many had experience of successful knowledge transfer. Renault's Formula 1 team started their operations with Amédée Gordini who had experience of designing Grand Prix cars. The option to run a turbocharged engine had been in the rules for many years, but nobody had dared to pursue it until Renault. It had secretly begun track testing with a 1.5-litre version of the turbo engine in 1976, and a short programme of races was scheduled for the following year.

### 5.2.2. Ford – Cosworth DFV Engine

FIA changed the rules in the 1965 season, raising the maximum engine capacity from 1.5 litre to 3.0 litre. Up to that point, Coventry Climax had been supplying Lotus with its engines, but they decided not to produce the higher capacity engine and as a result Lotus was forced to look elsewhere. Lotus founder Colin Chapman turned to Cosworth, a company founded by former Lotus gearbox engineer, Keith Duckworth and Mike Costin. Duckworth informed Chapman that while Cosworth can produce a grand prix engine, the firm would need funding for the associated development costs. Chapman secured this funding through Ford.

Dual Four Valve (DFV) type Ford V8 engine was introduced in June, 1967. Even though Brabham won the championship in 1967 (with the driver Denis Hulme) DFV type Ford V8 driven by Jim Clarke won the very first race it took part in at Zandvoort (Dutch Grand Prix). The DFV engine would go on to dominate the Grands Prix till the advent of turbocharged cars and to date remains one of the most radical innovations in Formula 1 (Floyd and Jenkins, 2001).

Ford-Cosworth DFV engine powered cars won 10 constructors and 12 drivers world championships in next 16 years without any major changes to bore and stroke or any major castings. Ford-Cosworth DFV engine powered cars won 65% of all Grands Prix in Formula 1 between its introduction in 1967 and its final appearance in 1983 against 10 other engine makers with as many as 30 different engine specifications (Cosworth Story, 2011). This highlights three important facets of alliances in Formula 1, as discussed by interviewees earlier;

- DFV alliance formation was driven by the need of a Formula 1 team's need to access external knowledge and technology.
- This need arose because of an external regulatory change.
- Alliance partners had a history of prior alliances.

Keith Duckworth and Mike Costin founded Cosworth in 1958. One of the earliest projects of Cosworth involved tuning of 1.1 litre Coventry Climax engine for sports cars. Over next few years, Cosworth took on a number of projects involving *tuning* or customisation of engines for a particular class of racing or private customers. Their first experience of competing in a FIA sanctioned series came with their customisation of the Ford's New Anglia 105E engine for the Formula Junior category (Burr, 2015).

This engine was an 8-port IL4 1.0 litre and had oversquared bore to stroke ratio (B/S) of 1.67 with a push road overhead valve system (bore diameter of 80.96 mm and stroke length of 48.42 mm.) It had a 3-main-bearing crank (Cosworth story,2013). Cosworth Formula Junior engine produced around 75 HP compared to the 39 HP of the stock unit. This was achieved using individual tuned inlets and exhaust systems and a long period camshaft (Cosworth story, 2013). The Cosworth engine won nearly half of all the races it took part in between 1960 – 1963 and dominated the erstwhile dominant Fiat engine cars in the category. Cosworth continued to work on the engine, and expanded the cylinder volume to 1.1 litre. The new larger capacity engine had some experimental features such as 50 degree downdraught inlet ports (Burr, 2015) and produced more power than the original variant.

Cosworth continued its collaboration with Ford and worked on single overhead cam for Ford Cortina engines in the Formula 2 category with 1.0 litre engines. Ford also provided Cosworth with funding for manufacturing a *Single Camshaft Type A* (SCA) engine with the same downdraught inlet ports as in Formula Junior engine. Cosworth continued to work on the engine and introduced fuel injection in second year of its development. By 1965, the engine was producing 140 HP and dominated its category by winning almost all races of the season (Burr, 2015; Cosworth story, 2013).

Lotus has been collaborating with Cosworth on their cars in the Ford Formula Junior, Formula 2, and Formula 3 category and were successful. This history of successful prior alliances in other categories led to Lotus collaborating with Cosworth on the new grand prix engine. Ford had provided funding for Cosworth's engines in the past and Lotus and Cosworth managed to secure funding for the new engine (£1.6 million at 2013 level, Cosworth story, 2013). The project involved not only a design for the new 3.0 litre V8 grand prix engine, but also design, development, and production of 1.6 litre Formula 2 engine for the 1967 season (Jenkins and Floyd, 2001).

Funding was used, in parts, to develop the Formula 2 Four Valve Type A (FVA) engine with four valves per cylinder (v/c) double overhead camshaft (DOHC) head on the Ford 'Cortina' 120E 1.6 litre block (Cosworth Story, 2013.) The funding for the 3.0 litre V8 grand prix engine was dependent on the success of the FVA engine in Formula 2. The new 4 v/c designs of the FVA was successful in its category and outperformed its competitors by delivering almost 40% more HP. FVA design accomplished this by generating higher brake mean effective pressure (BMEP) at a higher piston speeds with similar weight and price and HP ratio (Cosworth Story, 2013; Jenkins and Floyd, 2001).

Another distinguishing feature of FVA engine was the way the inlet flow was aimed at the opposite cylinder wall to produce a circular motion in the plane of crankshaft rotation which was then much amplified in velocity by the rising piston during compression. This is called 'tumble swirl' or barrel turbulence (Reeves et al., 1999). It produces a gain of the product volumetric efficiency (EV) and combustion efficiency (EC), the first element being reduced by the extra pressure loss to produce the swirl but the second element more than compensating for this through faster burning.

Duckworth believed that barrel turbulence was one of the, if not the most important feature in producing the superior FVA performance. Duckworth gave many interviews in the 70s and 80s explaining his design philosophy and the FVA and DFV engines, but when it came to the cylinder head (port shapes), he said he wished to keep it to himself as it was obvious that most people had not thought through the problem. Cosworth never patented the technology as that would have meant describing the phenomena and then it could have been adopted by competitors. This tendency to keep source of competitive advantage tacit and within individuals and not make it explicit by patenting or other forms of intellectual copyrights is a feature of Formula 1.

The Cosworth FVA dominated the F2 Championships from 1967 to 1971. The Cosworth FVA won 78% of all races that year against Ferrari's V6 and BMW's IL4 M12/2. FIA changed regulations for the 1972 season, and new 2 litre engines were introduced. The championship was won by a car using Ford Cosworth BDA-base engine, which was essentially a *production* version of FVA with a belt drive that connected it to the DOHC. The FVA engine was specifically developed for Brian Hart who modified his 1.85 litre BMW, and adapted it for the head/piston design of BMW's IL4 M12/6 2L F2 engine. He won the championships in 1973, 1974, and 1975.

FVA won another three Formula 2 championships between 1976 – 1984. In 1976, FIA had changed regulations Formula 2 category and engines and allowed 2.0 litre engines with six cylinders. BMW used this design of FVA engine and modified it by *destoking* it to 1.5 litre and fitting in turbochargers (Cosworth story, 2013.) This turbocharged engine, the M12/13, became first turbocharged engine to win the World Drivers' Championship in 1983, and ended the Ford Cosworth DFV domination.

Keith Duckworth started working on the design of DFV in March 1966 (Burr, 2015; Cosworth story, 2013). By this time, the FVA engine was already producing 200 HP in testing, and Duckworth decided to use the FVA head technology for the new V8 DFV. Duckworth opted for a V8 configuration instead of the then popular V12 and inline designs to achieve lower weight and higher mechanical efficiency (Burr, 2015).

FIA had mandated that Formula 2 engines be only 1.6 litre. FIA regulation and the physical dimensions of the cast-iron engine block led to Cosworth designing FVA with B/S of 1.24. The cast iron block was 85.72 mm, and the production size was 80.96 mm (Cosworth story, 2013.) DFV engine's bore diameter (80.674 mm) was slightly reduced from FVA's (80.96 mm). The stroke was reduced from 69.144 mm to 67.77 mm. These design changes were necessary to meet FIA's 3.0 litre regulation. Therefore; DFV ended up with a B/S of 1.323. DFV's combustion chamber volume was also reduced compared to FVA but it retained the flat-top piston configuration of the FVA. This resulted in valve interference angle being reduced to 32 degree though it did allow the downdraught to be increased to 35.

The barrel turbulence feature of the FVA was retained in the DFV design. Duckworth kept this feature hidden for many years (Burr, 2015). FVA and DFV shared; valve sizes, lifts, timings, pistons (albeit with improved ring materials made from stainless steel with molybdenum fillings to prevent scuffing), fuel injection system (mechanically driven in DFV instead of the electrically driven system in FVA), and the exhaust system (Cosworth story, 2013)

DFV was designed solely by Keith Duckworth with Mike Hall (Former BRM designer) working on the side accessories from Duckworth's design schemes. The entire process only took nine months. Duckworth explained the relatively short time scale for the development of DFV because of his experience of working on the FVA engine (Burr, 2015; Cosworth story, 2013). The development, and success, of the DFV engine can be attributed to one individual with requisite knowledge and expertise, Keith Duckworth (Burr, 2015).

The DFV engine was developed in response to the new regulations on engine size. DFV was a huge step in technological innovation. Chapman designed Lotus 49 around the DFV engine and employed it as a major part of the structure to reduce the weight and make car lighter (Floyd and Jenkins, 2001). Ford did not award Lotus with the exclusive rights for use of the engine, and made it available to other teams in F1. McLaren and Matra were the first teams to take advantage of this in 1968 using the Ford Cosworth DFV and Brabham followed in 1969. This led to the era of 'Ford powered kit-cars' in 70s where F1 became dominated with Cosworth DFV engine, gearboxes manufactured by Hewland Engineering (Beck-Burridge and Walton, 2000) and chassis and suspension designed by the constructors. Arrival of DFV 'kit cars' also put the vertically integrated constructors such as Ferrari and BRM who built their own engines and gearboxes at a disadvantage.

Cosworth engineers were former Lotus employees and had experience of working with race engines and had used this set of knowledge in past projects and were an expert in the knowledge field (Szulanski, 1996 and Szulanski, 2000) enabling them to better articulate the knowledge required. Also, DFV was based around the same engine block as FVA. Early involvement of

Ford in development of DFV engine was limited to funding but gradually it evolved into wider areas and Ford worked with Cosworth and used the DFV in its sports racing car, P68 in BOAC 500 race at Brands Hatch in Kent in 1968. (In context of FVA)

Cosworth has been working exclusively for Lotus and used that knowledge and experience to design the DFV engine demonstrating an ability to abstract the knowledge from the day-to-day context (Sobek et al., 1998). Cosworth founder, Keith Duckworth had worked at Lotus in the past and was approached by Colin Chapman for the development of the DFV engine. He understood the background, existing technologies, appropriate contextual information and nomenclature to develop the new engine with the funding from the Ford.

The process of knowledge transfer was also facilitated by the parallel development of Lotus 49 and the DFV engine and Cosworth and Lotus shared technical information and requirement at all times. Lotus founder, Colin Chapman was heavily involved with the projected and along with Cosworth founder, Keith Duckworth who was also a former Lotus engineer. Chapman designed Lotus 49 around the DFV engine and employed it as a major part of the structure to reduce the weight and make car lighter (Floyd and Jenkins, 2001).

Constructors in Formula 1 had always been involved with automotive manufacturers, and with the success of Ford Cosworth DFV engine, many had experience of successful knowledge transfer highlighting how recipient firm's experience of successful collaborations in the past can play a constructive role in knowledge transfer process (Fosfuri and Tribo, 2008). Duckworth established strict rules for the maintenance of DFV engines. DFV engines were only worked and repaired in the Cosworth workshop. When the numbers of engines needing repairs and maintenance became too large in 1970s, Cosworth allowed a certain number of outside workshops to perform repairs and maintenance work, but only with the Cosworth spares. Cosworth workshop would often return the DFV engine after maintenance work with the comment that "*It is better to be un-informed than ill-informed*" (Burr, 2015: 122). Cosworth employed this approach to protect their core competencies and ensure that innovations like 'barrel turbulence' continue to provide them with the technical advantage over their competitors.

Cosworth could convey this set of knowledge to others (Mietzel, 2007, cited by Schulze et al., 2014) and the other firms were able to apply the set of knowledge independently (Cummings and Teng, 2003) due to the technical competence of engineers working at Cosworth and Formula 1 teams. Ford also used variants of the DFV engine in Formula 1 and North American auto racing championships. DFL variant was particularly successful in LeMans.

Ford and Cosworth took their relationship forward with Cosworth developing a dual overhead camshaft 16-valve inline four-cylinder engine for road use in the Ford Escort, demonstrating one of the key aspect of successful knowledge transfer, that is the recipient firm is satisfied with the set of knowledge (Cummings and Teng, 2003). Key lessons from this successful collaboration include the importance of individual relationships in knowledge transfer and alliances, and the importance of keeping source of competitive advantage tacit.

### *5.2.3. Ferrari: Brawn Era*

After winning two consecutive drivers' world championship, Michael Schumacher left Benetton to join Ferrari in 1996. Rory Byrne and Ross Brawn followed Schumacher and left Benetton to join Ferrari as chief designer and technical director respectively in 1997.

The 1996 and 1997 seasons saw Williams' FW18 and FW19 cars winning the championship, in large parts due to Williams' technical director, Adrian Newey. Newey exploited a regulation loophole in later stage of 1995 season, moving the diffuser to the top of the plank allowing for a bigger exist area thus creating a more powerful diffusion in FW17B. Newey also designed a stepped gear arrangement for the gearbox. This allowed for extra clearance space and helped the team to hide the change in the position of diffuser. This approach of keeping innovations hidden, and not filing patents or intellectual property right claims, for competitive advantage is a characteristic of Formula 1.

Newey left Williams at the end of 1996 season and remained on the 'gardening leave' for the 1997 season before joining McLaren for the next season. But his incremental design innovation allowed William-Renault FW19 to stay ahead of the competition from Ferrari. Ferrari F310B, designed by John Barnard, was developed with Byrne and Brawn, and the car remained competitive with Williams' FW19 but the championship was won by Williams (albeit only in the last race.)

Jenkins and Tallman (2015) have argued that recruitment of Schumacher allowed Ferrari to not only have access to a world class driver for the first time since departure of Alain Prost in 1991, it also allowed the team to tap into the knowledge of individuals that Schumacher brought with him from Benetton (Ross Brawn and Rory Byrne.) Jean Todt also played an important role by shielding the team from corporate interference from the parent company. This resulted in a transformation on the engineering capability of Ferrari who had been struggling to build John Barnard's designs as recently as the last season because of lack of technical capability.

The 1998 season also saw FIA changing technical regulations, reducing the track width and introduction of grooved tyres to reduce mechanical grip and bring down speed to 'reduce risk'. Renault pulled out of their alliance with Williams in that season and with the departure of one of the best Formula 1 car designers in form of Adrian Newey, Williams were not able to match their performance of last two seasons. The Newey designed McLaren MP4-13 won the championship that year.

The MP4-13 had a lower nose than other cars to lower the centre of gravity, thus compensating for loss in mechanical grip from grooved tyres. McLaren MP4-13 used the Mercedes Ilmor designed engine, using aluminium and beryllium alloy for piston and cylinder lining. Beryllium played a critical role in Mercedes engine delivering more power than the Ferrari engine. Mercedes engine in McLaren revved at the same rate as Ferrari engine but due to elastic properties of beryllium, could make longer stokes and deliver more power than the Ferrari engine. Ferrari and other teams were not aware of how McLaren and Mercedes were accomplishing that despite having same revs per minutes (rpms) as the Ferrari engine. McLaren Mercedes also switched to Bridgestone tyres whereas Ferrari stuck with Goodyear tyres, deepening their collaboration with the tyre supplier.

The Byrne designed Ferrari F300 was not as fast as Newey's McLaren MP4-13 as the start of the 1998 season but by the end of the season, engine development at Ferrari had paid off and Ferrari secure three consecutive poles to finish the season. 1999 and 2000 saw Ferrari developing its vehicle dynamics facilities and research and development group (Brawn and Parr, 2016). Bridgestone started supplying tyres to all teams from 1999 season, ending whatever technical advantage McLaren had because of their tyres. Ferrari won the constructor world championship that season but McLaren's Mikka Hakkinen won the driver's world championship.

The 2000 season saw the first Ferrari Formula 1 car that was designed and built under Brawn and Byrne team and was not compromised in any way by lack of skilled resources and facilities.

The Ferrari F1-2000 had its '*vee'* angle increased by ten degrees to 90' allowing for lower centre of gravity. This allowed for more stability and control. Schumacher became first Ferrari driver to win the world championship that year since 1979.

FIA introduced another set of regulation in the year 2001, banning use of beryllium. Beryllium is a highly carcinogenic and poisonous metal. The FIA ban led to Mercedes Ilmor engine losing its technical advantage over Ferrari. Newey said that the 2001 engine had no more power than the 1998 Mercedes-Ilmor engine as it became challenging, and cost prohibitive, to find a substitute for beryllium with similar elastic properties. The FIA also reintroduced *traction control* in 2001 season. Ferrari scored more point than McLaren and other teams after the introduction of traction control halfway through the season. This continued in the 2002 season which was dominated by the Ferrari F2002 which won fifteen grands prix out of the nineteen that it took part in 2002 and 2003.

Newey believed that McLaren car development had not been fast enough to react to changes in regulation and Ferrari challenges and it was *system driven* thinking which made it difficult for McLaren to win grand prix (Motorsport, 2016). McLaren's approach to car design relied on hierarchy of systems and the relationship between them, and Newey believed that that made McLaren slow to react to changes. The Newey designed MP4-18 for 2003 season did not pass FIA tests, including the crucial side impact crash tests and crashed several times during testing. McLaren decided to race MP4-17D, an evolved version of 2002 car for the 2003 season. This highlights how regulations can affect the development process and innovation within the inter-organisational network.

FIA issued another notice for sporting regulation change late in the 2003 season. FIA mandated single lap qualifying with *parc ferme*. This essentially meant that Ferrari could not alter the weight distribution of the F2003 GA between the qualifying and the race. Ferrari with its longer wheelbase needed changes to its weight distribution (front biased) for fastest qualifying times and race times. These changes allowed McLaren to compete with Ferrari in the final round of 2003 season but Byrne and Brawn redesigned the 2004 car to cope with the new *parc freme* regulations. New V10 in the Ferrari F2004 weighed only 90 Kgs and produced 900bhp, that is 100bhp more than the Ferrari F2000 engine.

Ferrari's domination of 2004 forced McLaren and Newey to react with another radical design change, which resulted in the McLaren MP4 20. To cope with Newey's design changes, Mercedes Ilmor had to lower the crankshaft height which affected the reliability of the car. Last two seasons had seen McLaren and other teams moving to Michelin tyres with the exception of Ferrari which deepened its partnership with Bridgestone. FIA banned tyre changes for the 2005 season which created problems for Bridgestone tyres' rigid sidewall design. This design had the effect of forcing the tread to move more than the full radial flexi sidewall design of Michelin tyres used by other teams.

This regulation change proved to be particularly advantageous for the Renault factory team which had been developing a rear weight bias car that exploited the longitudinal grip offered by full radial flexi sidewall Michelin tyres. Renault's Fernando Alonso won the championship that year despite the McLaren MP4 20 being faster. This illustrates the importance of system integration in Formula 1. One component (engine in this case) on its own cannot sustain team performance over a season, and the whole package, or *alliance* as interviewees called it, needs to perform.

The 2006 season saw a major regulation change (Jenkins, 2014) with the end of V10 engines in Formula 1. V8 engines were introduced to Formula 1 and tyre changes were permitted again. Bridgestone changed their rigid sidewall design and adapted full radial flexi sidewall design of Michelin tyres. Adrian Newey left McLaren that season and joined the Red Bull Racing. Competition for Ferrari came from the Bob Bell designed Renault R26. Renault and a few other teams were using 'tuned mass damper' in the nosecone of their cars in the 2006 season to keep tyres in contact with the surface when going over kerbs and in corners. Renault had in-effect designed the R26 chassis around the tuned mass damper.

FIA banned the use of tuned mass damper by the Turkish grand prix and Renault struggled to win point in next two grands prix. It was considered a controversial decision by FIA since the FIA was consulted about the system during its development. Despite the setback, Renault managed to win the world constructor and driver championship that season.

The 2007 season saw Ross Brawn, Rory Byrne, Jean Todt, and Michael Schumacher leaving Ferrari. Ferrari's CEO Luca di Montezemolo decided to replace the technical direction, chief designer, and principal position with *home grown talent.* Stefano Domenicali became team manager. The structures and programs put in place by Brawn and team carried on, partly due to the inertia, and kept team performance high but Domenicali was not empowered to make decisions such as long term investment for new technical projects, or play the role of gatekeeper between the team and the management as done by Jean Todt.

Ferrari has failed to win drivers' championship since the 2007 season and constructors' championship since 2008 season. This goes on to highlight the importance of individuals, especially those with access to novel knowledge and way of doing things, to competitiveness of a team.

#### 5.2.4. Case Study themes

Key themes that have emerged from case studies are;

- There are key individuals who have more influence on a team's performance than others.
- These individuals either bring the engineering know-how with themselves or a network to access the expertise.
- Formula 1 teams pursue knowledge transfer to gain competitive advantage.
- This knowledge often resides within individuals, especially since most technical gains and innovations are never patented and often, kept secret.
- Formula 1 teams have a non-traditional management structures.
- Regulations are key externalities that motivate teams to get into alliance and pursue knowledge (and individuals with the said knowledge) to successfully respond to these challenges.
- Formula 1 teams face rapid changes in product and process technology, competitors' performance and strategic actions, and regulations. Formula 1 is a fast clockspeed industry.
- Formula 1 teams are engaged in constant improvement of components and technologies.

These key findings of case studies support and complement interview findings as shown in table 12. These qualitative findings highlight the key role played by individuals in the inter-organisation network of Formula 1. Certain key individuals, such as Michael Schumacher and Adrian Newey, have a positive impact on organisation performance. The next chapter provides the social network analysis of the Formula 1 network and helps visualise the importance of these nodes.

*Table 20 Case Study and Interview Findings (Source: Interviewees and case studies)*

| **Case Studies**<br><br>**Interview findings** | **Renault RS01: The Yellow Teapot** | **Ford – Cosworth DFV Engine** | **Ferrari: Brawn Era** |
|---|---|---|---|
| Individuals are key exponents of knowledge and impact organisational performance. | Andre de Cortanze and Jean-Pierre built the RS01 which allowed Renault to enter the Formula 1. | Colin Chapman brought funding for Cosworth, facilitating the building DFV engine which went on to win more 10 constructor world championships and 12 driver world championships. | When Schumacher joined Ferrari, he brought Rory Byrne and Ross Brawn from Benetton. Ferrari went on to win five drivers' and six constructors' world championship in next ten years. Similarly, Adrian Newey's move to McLaren resulted in McLaren wining two consecutive world championships while Williams, his former team, lost the world title. |
| Innovations and technological improvements are not patented and teams instead rely on knowledge residing within individuals. | Renault relied on Andre de Cortanze and Jean-Pierre Jabouille to adopt the 2.0 litre LeMans turbocharged engine for Formula 1. | Duckworth did not disclose barrel turbulence, and tried to restrict DFV engine maintenance to keep the design confidential. | McLaren and Mercedes Illmor did not discuss their use of byrillium in pistons. |
| Formula 1 car is an alliance. | Renault RS01 was result of an alliance between grand prix driver/designer and Renault Sports Racing. | DFV engine came about because of alliance between Lotus, Ford, and Cosworth | Performance of McLaren MP4-13 was dependent on the Mercedes-Illmor engine and Newey's designs. |
| Teams are driven by knowledge | Renault's involvement in Formula 1 allowed them to develop turbocharging technology for application in their road going cars. | Lotus' Chapman sought Cosworth, and funding from Ford for the DFV engine because the team lacked the knowledge to build the engine. | Schumacher and Todt pursued Ross Brawn and Rory Byrne for their expertise in engineering and design. |
| Required knowledge is accessed via movement of individuals | Francois Castaing, designer behind turbocharged Renault RS10, joined Renault from Gordini, after the former took over the latter. | Relationship between Chapman and Duckworth (who had worked at Lotus) was key for the development of DFV. | Ferrari benefited in its technological capability via movement of Ross Brawn and Rory Byrne. |
| System integration is key for competitive advantage | Castaing and Jabouille's experience of engine and car design was key for Renault's F1 program. | Lotus won world championship with the DFV engine because of the deep integration between the engine development and the Lotus 79. | McLaren lost the championship to Renault in 2005 despite having the faster car, because Renault's car performed better as a package |
| Regulation changes drive knowledge transfer through technological discontinuities | Renault RS01 was introduced only after FIA changed regulations allowing turbocharged cars. | DFV engine was developed in response to changes in regulations. | Beyrillium based piston, a key part of Mercedes Illmor engine in McLaren, was banned by FIA, resulting in McLaren losing their advantage over Ferrari. |

# Chapter 6. Social Network Analysis: Quantitative Analysis

Formula 1 network for 1992 – 2010 is shown in figure 9. The figure shows all participating nodes in Formula 1 between 1992 and 2010, and all the edges. There are 976 nodes connected through 26, 717 edges within the Formula 1 network for the period under consideration. The figure shows all the nodes; drivers, engineers, technical directors, design directors, team principals, and team owners in the current season.

An edge between two nodes imply that they have either worked together in the same team in the past or are working together in the present. The size of the node indicates its degree that is the number of connections that the node has with other nodes. The higher the *degree*, bigger the size of the node.

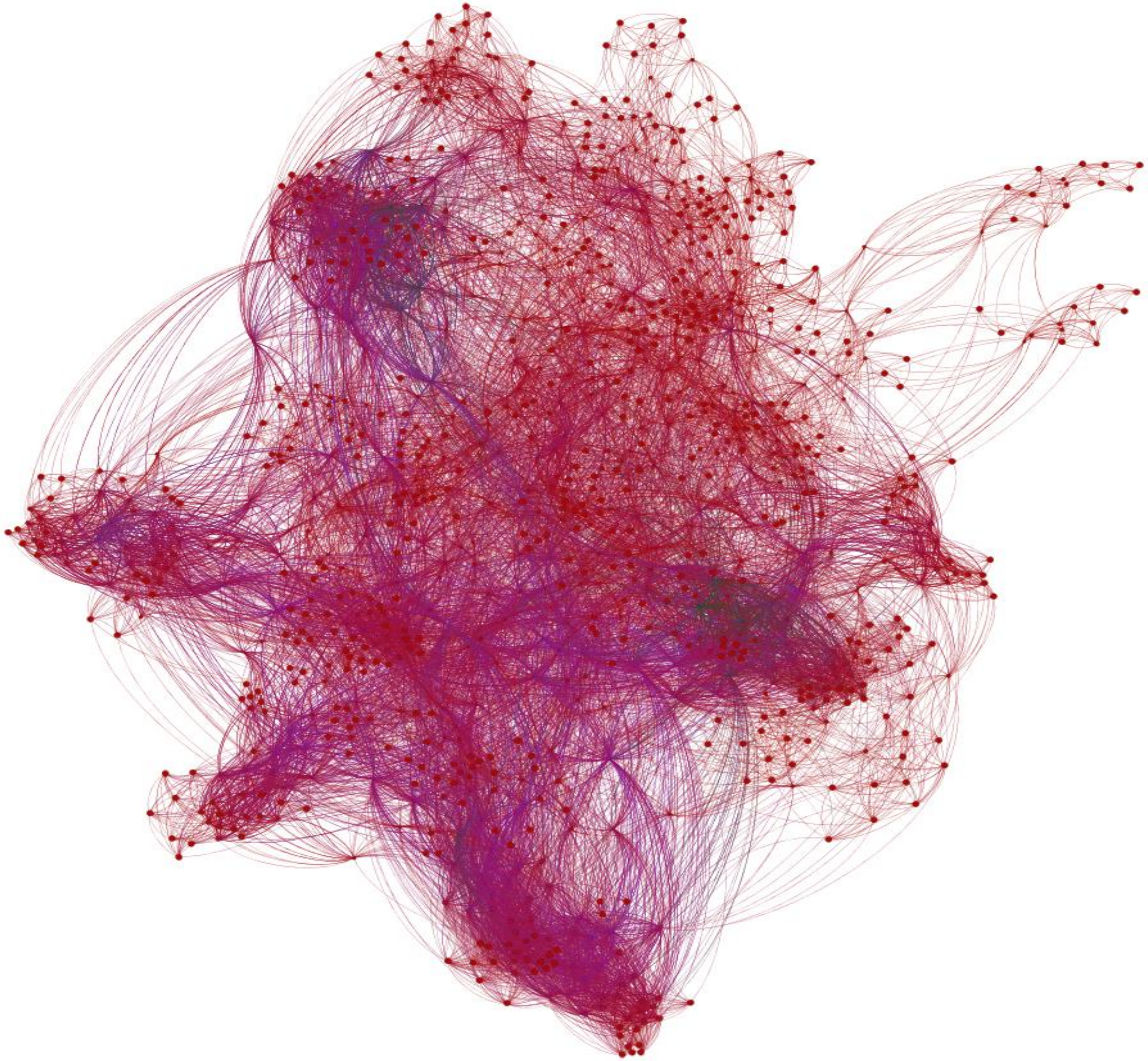


*Figure 9 Formula 1 Network Graph 1992 – 2010*

Figure 9 gave an overview of the wide network of Formula 1 and its interconnectedness. In the network, even the most peripheral nodes are connected and can reach any other node within the network via three edges on average.

Table 19 highlights these metrics and gives a yearly overview of node level and network level metrics in Formula 1 network for the period 1992 – 2010. An average degree of 57 implies that on average, every individual in Formula 1 is connected to 57 other individuals working in the industry. The interconnected nature if further highlighted by 'higher than average' density for a real-life network (Newman, 2003; Albert and Barabasi, 1999). The network diameter suggests that even the most distant placed nodes can reach each other through five path lengths.

The graph density of the Formula 1 network is 0.058 which is high for a real-life network (Mishra et al., 2017) and highlights the densely interconnected nature of the industry, as shown in the network graph and also reflected in case studies and interviews. Similarly, a high clustering coefficient and short average path lengths, indicate that network is rich in clusters, as expected of an industry like Formula 1, and has high information flows.

## 6.1. Small World

Watts and Strogatz (1998) defined small world networks as networks that are *highly clustered, like regular lattices, yet have small characteristic path lengths, like random graphs.* Formula 1 network does exhibit this network phenomena with high clustering coefficient and low average path length. This essentially implies that Formula 1 network has clusters or regions of specialization (such as engine suppliers or electrical systems manufacturer) with distributed processing across the network through connected nodes (people), resulting in an efficient knowledge transfer process.

*Table 21 Metric Table 1992- 2010*

| **Network Wide Metrics** | **1992 - 2010** |
|---|---|
| Nodes | 976 |
| Edges | 26, 717 |
| Average Degree | 56.59 |
| Network Diameter | 5 |
| Graph Density | 0.058 |
| Average Clustering Coefficient | 0.763 |
| Average Path Length | 2.659 |

Given the size and density of the Formula One network (table 20) it is possible to construct an equivalent random graph. The clustering coefficient and path length can be calculated using equations 4 and 5. These can then be compared with the actual network as shown in table 16.

*Table 22 Comparison of Formula 1 network to random graph; demonstrating small world nature.*

| **Metric** | **Corresponding Random Network** | **F1 network** | **Ratio** | **Small World Coefficient Q** |
|---|---|---|---|---|
| Clustering Coefficient | 0.036 (equation 4, Section 3.5) | 0.763 (table 20) | 21.194 (equation 2, Section 3.5) | 13.585 (equation 1, Section 3.5) |
| Path Length | 1.706 | 2.659 | 1.56 | |

| | | | | |
|---|---|---|---|---|
| | (equation 5, Section 3.5) | (table 20) | (equation 3, Section 3.5) | |

The Formula 1 network has a relatively high clustering coefficient compared to its average path length, with the latter being more similar to a random network. Thus the small world quotient (equation 1; the ratio of clustering ratio to path length ratio) is much greater than 1 and indicates that the Formula 1 network has a small world nature.

This essentially implies that Formula 1 network has clusters or regions of specialization (such as engine suppliers or electrical systems manufacturer) with distributed processing across the network through connected nodes (people), resulting in an efficient knowledge transfer process. Small world networks also influence innovation (Verspagen and Duysters, 2004, Balcon et al., 2004, Cowan et al., 2007, Gay and Dousset, 2005) and this points to the inherent innovativeness of Formula 1.

## 6.2. Top and Bottom Nodes

The following table lists the top 30 nodes in the network, ranked according to their degree centrality.

*Table 23 Metric table for top 30 nodes (according to their degree)*

| Nodes | Degree | Betweenness Centrality | Page Rank | EigenVector Centrality |
|---|---|---|---|---|
| Pat Symonds | 317 | 5022 | 0.004 | 0.713 |
| Luca Di Montezemolo | 315 | 4057 | 0.004 | 0.984 |
| Flavio Briatore | 313 | 8908 | 0.004 | 0.689 |
| Alan Permane | 303 | 5515 | 0.004 | 0.65 |
| Rory Byrne | 300 | 3528 | 0.004 | 1 |
| Mike Gascoyne | 299 | 23470 | 0.005 | 0.423 |
| Michael Schumacher | 294 | 5060 | 0.004 | 0.957 |
| Jock Clear | 294 | 5891 | 0.004 | 0.53 |
| Luca Badoer | 291 | 13090 | 0.004 | 0.89 |
| Steve Nielsen | 291 | 7726 | 0.004 | 0.556 |
| Mattia Binotto | 283 | 9047 | 0.004 | 0.787 |
| Ron Dennis | 278 | 3374 | 0.004 | 0.404 |
| Neil Oatley | 278 | 3375 | 0.004 | 0.404 |
| Rubens Barrichello | 275 | 18516 | 0.004 | 0.647 |
| Ross Brawn | 274 | 5606 | 0.004 | 0.86 |
| Luigi Mazzola | 273 | 3730 | 0.004 | 0.885 |
| Frank Williams | 270 | 5033 | 0.004 | 0.376 |
| Stefano Domenicali | 257 | 777 | 0.003 | 0.902 |
| Jean Todt | 256 | 1473 | 0.003 | 0.852 |
| Tim Densham | 253 | 8390 | 0.004 | 0.444 |
| Giancarlo Fisichella | 252 | 17333 | 0.004 | 0.476 |
| Adrian Newey | 250 | 7640 | 0.004 | 0.372 |
| Andrew Alsworth | 246 | 5153 | 0.003 | 0.504 |
| Mark Smith | 246 | 10335 | 0.003 | 0.428 |
| Patrick Head | 240 | 3233 | 0.004 | 0.351 |
| Dickie Stanford | 240 | 3786 | 0.004 | 0.349 |
| Ron Meadows | 236 | 1800 | 0.003 | 0.447 |
| Jarno Trulli | 235 | 17180 | 0.004 | 0.291 |
| Craig Wilson | 233 | 5660 | 0.003 | 0.422 |

When movement of these higher ranked nodes is plotted with team performance, it can be observed from the movement of nodes that a positive co-relation exists between rise in team performance and movement of these 'high metric value' individuals. In 2002 season, BAR Honda scored less than 10% of constructor championship points but as can be seen in the figure 10, with involvement of Jock Clear and Andrew Alsworth, their performance rises and within next two season they score almost 20% of all constructor championship points and are second in the world championship.

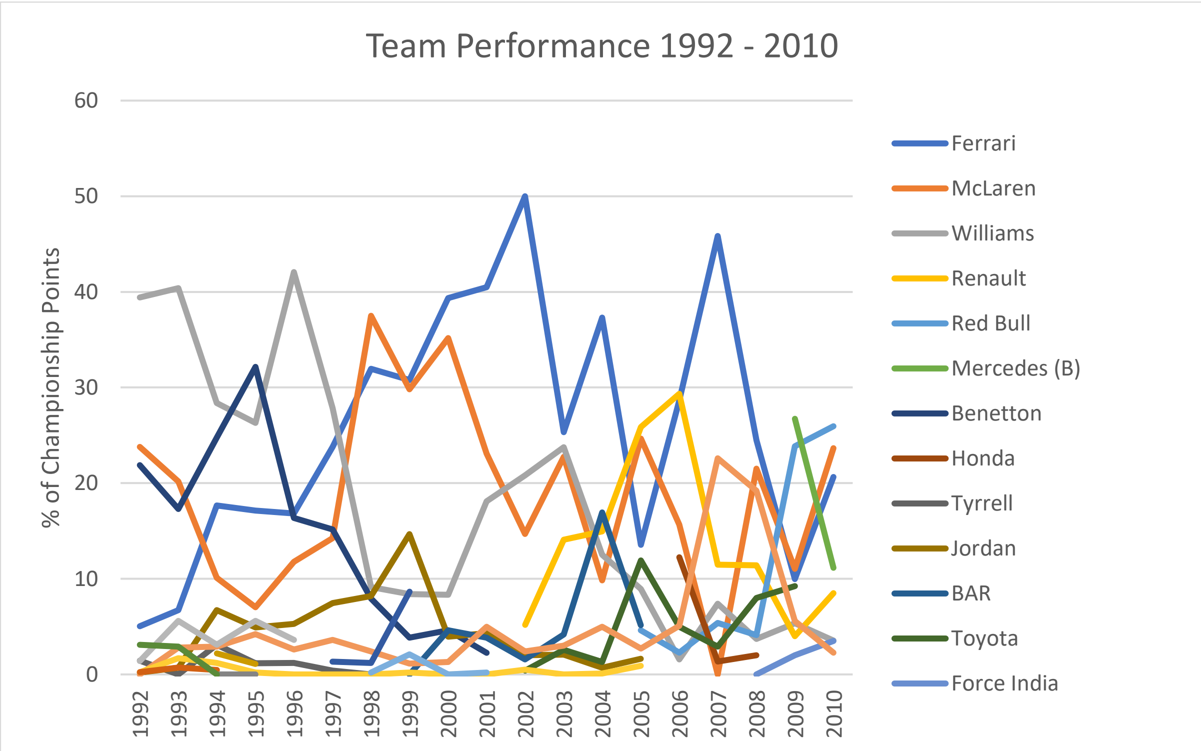



*Figure 10 Team Performance*

To take three specific examples, beginning with the case of Andrew Alsworth, he spent seven years at Benetton (1992-1998). Benetton score 21.87% of total constructor world championship points in 1992, and only 7.93% in 1998 when Andrew Alsworth left the team for BAR. The seven-year period saw Benetton's performance deteriorate. When Alsworth joined BAR in 1999, the team could not score any points in the world championship but by the time he left the team (2005), BAR scored 11.92% of world championship points. In 2006, BAR was taken over by Honda and run as a factory team till 2008, when they pulled out of the sport. At that point, the team was taken over by Ross Brawn and ran with essentially the same staff. During Andrew Alsworth's time at Honda and Brawn, team went from scoring 5.15% of championship points in 2006 to 26.73% of championship points in 2009. Alsworth's net contribution to performance of Benetton between 1992 and 1998 is -1.991, BAR between 1999 and 2005 is 1.70, Honda/Brawn between 2006 and 2009 is 5.395.

Adrian Newey was car designer for Williams between 1992 and 1996. Williams won four championships in that period, and their percentage of points scored in constructors' world championship went from 39.42% in 1992 to 42.07% in 1996. Newey joined McLaren in 1997 season, and the team scored 14.25% of championship points that season. When Newey left McLaren in 2005, team scored 24.66% of championship points. Newey started working at Red Bull in 2006, and the team scored only 2.28% of championship points that season. In 2010, Red Bull scored 25.92% of championship points. Newey's time at different teams resulted in more championship points. Newey's net contribution to performance of Williams between 1992 and 1996 is 0.53, McLaren between 1997 and 2005 is 1.157, and Red Bull between 2006 and 2010 is 4.728.

Ross Brawn was involved as technical director at Benetton between 1992 and 1996. Benetton score 21.87% of championship points in 1992 season. For the 1996 season, Brawn's last season at Benetton, the team scored 16.35% of championship points. Brawn joined Ferrari in 1997 season, and the team scored 23.78% of total championship points that season. In 2006, when Braw left Ferrari, team scored 28.63% of championship points. Brawn spent next two years at Honda, before taking over the team after Honda pulled out of the Formula 1. Honda scored only 1.35% of championship point in 2007 season, and in 2009 season, the team scored 26.73% of championship points. Team was taken over by Mercedes for the 2010 season, and team scored 11.15% of championship points in its debut season. Brawn's net contribution to performance of Benetton between 1992 and 1996 is -1.104, Ferrari between 1997 and 2006 is 0.485, Honda/Brawn between 2007 and 2009 is 8.46, Mercedes for the 2010 season is 11.15.

It is interesting to note that nodes such as Luca Badoer are in top 30 most connected nodes. Luca Badoer was the test and reserve drive for Ferrari between 1998 and 2010. Ferrari won six world championships in this period. Luca Badoer, a reserve and test driver, stands out in the network visualisation whereas it is difficult to identify his contribution and importance within the qualitative analysis carried out in the interviews and case studies. This highlights the suitability and comprehensive nature of the network analysis of the Formula 1 network.

The net contribution of these nodes is positive, cumulatively, whereas in case of the bottom 30 nodes, the trend is either for negative or 0 net contribution to team's performances. The following table lists bottom thirty nodes listed according to their degree.

*Table 24 Metric table for bottom 30 nodes (according to their degree)*

| Nodes | Degree | Betweenness Centrality | Page Rank | EigenVector Centrality |
|---|---|---|---|---|
| Eric Van De Poele | 5 | 0 | 0 | 0.004 |
| Denis Nursey | 5 | 0 | 0 | 0.004 |
| Ray Boulter | 5 | 0 | 0 | 0.004 |
| Taki Inoue | 5 | 0 | 0 | 0.001 |
| John Creak | 5 | 0 | 0 | 0.001 |
| Hideki Noda | 5 | 0 | 0 | 0.003 |
| Nicholas Wirth | 5 | 0 | 0 | 0.003 |
| Richard Taylor | 5 | 0 | 0 | 0.003 |
| Domenico Schiattarella | 5 | 0 | 0 | 0.003 |
| Trevor Sheumack | 7 | 0 | 0 | 0.003 |
| Andrea Chiesa | 7 | 0 | 0 | 0.003 |
| Glanfranco Palazzoli | 7 | 0 | 0 | 0.003 |
| Peter Wyss | 7 | 0 | 0 | 0.003 |
| Jean-Pierre Paoli | 7 | 0 | 0 | 0.001 |
| Robert Dassaud | 7 | 0 | 0 | 0.001 |
| Eric Guilloud | 7 | 0 | 0 | 0.002 |
| Michel Tifu | 7 | 0 | 0 | 0.002 |
| Darry Hindenoch | 7 | 0 | 0 | 0.003 |
| Eric Vullemin | 7 | 0 | 0 | 0.003 |
| Jean-Pierce Chatenet | 7 | 0 | 0 | 0.003 |
| Erik Bernard | 7 | 0 | 0 | 0.003 |
| Shinji Nakano | 7 | 0 | 0 | 0.005 |
| Henny Vollenberg | 8 | 0 | 0 | 0.003 |
| Brendan Gribben | 8 | 0 | 0 | 0.003 |
| Dave Luckett | 8 | 0 | 0 | 0.003 |
| Gordon Coppuck | 8 | 0 | 0 | 0.003 |

| | | | | |
|---|---|---|---|---|
| Philippe Alliot | 8 | 0 | 0 | 0.001 |
| Tino Holloway | 8 | 0 | 0.001 | 0.001 |
| Jerry Bond | 8 | 0 | 0.001 | 0.001 |
| Carlo Gancia | 8 | 0 | 0 | 0.007 |

For instance, Nicholas Wirth spent two seasons with Simtek (1994-1995). The team score no points in either season. Wirth joined Benetton in 1996, and the team scored 16.35% of the championship points that season. Wirth left in 1999, and the team scored 3.85% of total points in the championship. Wirth's net contribution to the team performance of Simtek is 0, and for Benetton is -3.125. Looking at other bottom nodes, Such as Richard Taylor and Domenico Schiattarella, it can be observed that their team (Simtek) did not score any points during their stint. It can be deduced that nodes with higher degree have a positive influence on team performance, as can be observed in figure 7 where the movement of three highly connected nodes, Ross Brawn, Adrian Newey, and Andrew Alsworth is mapped and compared against the normalised team performance.

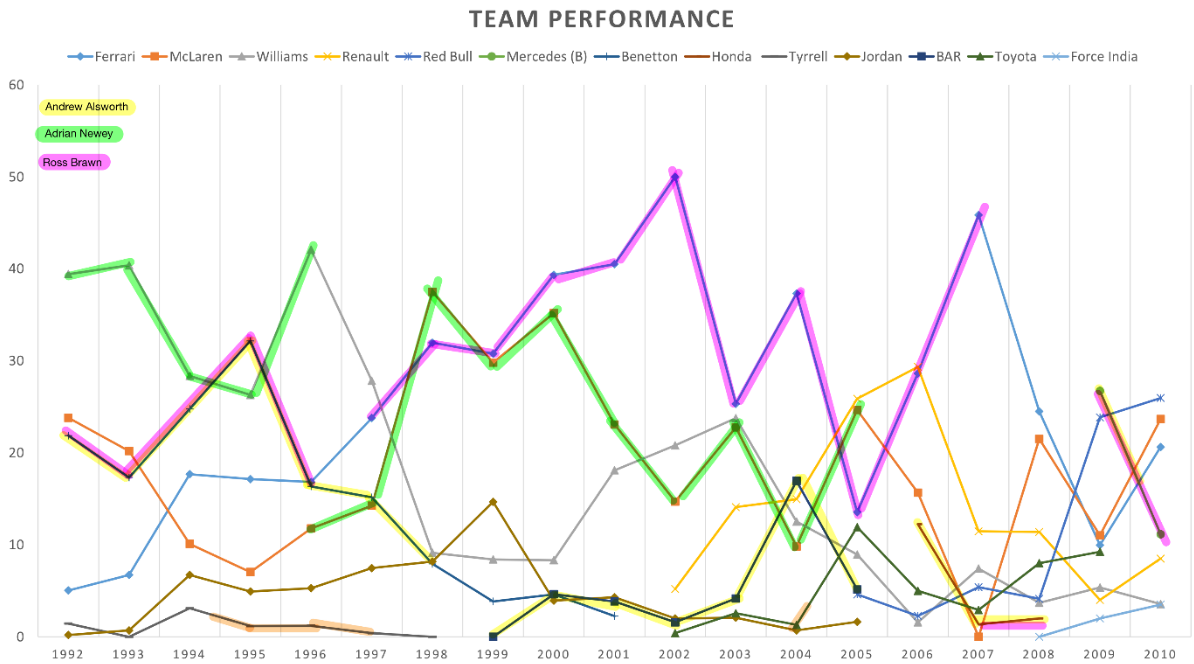



*Figure 11 Effect of movement of highly connected nodes on team performance*

To examine the effect more rigorously, analysis was extended. Table 17 and Table 18 lists the top thirty highly connected and bottom thirty least connected nodes respectively. To calculate effect of a node on a team's performance, the net performance point (that is the difference between team performance when the node left the team and when node started working at the team) was divided by the number of years spent by the node at that team as shown in table 24 for the node, Mike Gascoyne.

*Table 25 Node effect on team performance*

| Mike Gascoyne<br><br>Constructor | Year Joined | Year Left (after finishing the season) | Total Number of Years (Y) | E (Effect on Performance) = $TP_l$ - $TP_j$ | Cumulative Effect on Performance ( E / Y) |
|---|---|---|---|---|---|
| Sauber | 1992 ($TP_j$) | 1993 ($TP_l$) | 2 | | |
| Team Performance (TP) | 0 | 2.8 | | 2.8 | **1** |
| | | | | | |
| Tyrrell | 1994 ($TP_j$) | 1997 ($TP_l$) | 4 | | |
| Team Performance | 3.1 | 0.4 | | -2.7 | **-0.675** |
| | | | | | |
| Jordan | 1998 ($TP_j$) | 2000 ($TP_l$) | 3 | | |
| Team Performance | 8.18 | 3.94 | | -4.24 | **-1.413** |
| | | | | | |
| Benetton/Renault | 2001 ($TP_j$) | 2003 ($TP_l$) | 3 | | |
| Team Performance | 2.26 | 14.1 | | 11.84 | **3.947** |
| | | | | | |
| Toyota | 2004 ($TP_j$) | 2006 ($TP_l$) | 3 | | |
| Team Performance | 1.3 | 5 | | 3.7 | **1.233** |

Similarly, for a bottom placed node, Taki Inoune, the cumulative effect on performance is calculated as follow,

*Table 26 Node effect on performance*

| Taki Inoune<br><br>Constructor | Year Joined | Year Left (after finishing the season) | Total Number of Years (Y) | E (Effect on Performance) = $TP_l$ - $TP_j$ | Cumulative Effect on Performance ( E / Y) |
|---|---|---|---|---|---|
| Simtek | 1994 ($TP_j$) | 1994 ($TP_l$) | 1 | | |
| Team Performance | 0 | | | 0 | **0** |
| | | | | | |
| Footwork | | 1995 ($TP_l$) | 1 | | |

| | | | | | |
|---|---|---|---|---|---|
| Team Performance | 2.2 (1994) | 1.1 | | -1.1 | **-1.1** |

It is important to note that each node's performance generates a number of data points in form of positive or negative effect on the team performance for their association with each team. So for example, in case of Mike Gascoyne in table 19, there are five data points, *1*, *-0.675*, *-1.413*, *3.947*, and 1.233. Similarly, Taki Inoune's association with Simtek and Footwork generates two data points, *0* and *-1.1*.

The analysis (figure 7) shows that the movement of top 30 nodes in the network (organised according to their degrees), tends to produce a positive effect on performance. When compared with results of the bottom 30 nodes, it can be observed that nodes with lower degrees and connections tend to either have no effect on a team's performance or have negative effect.

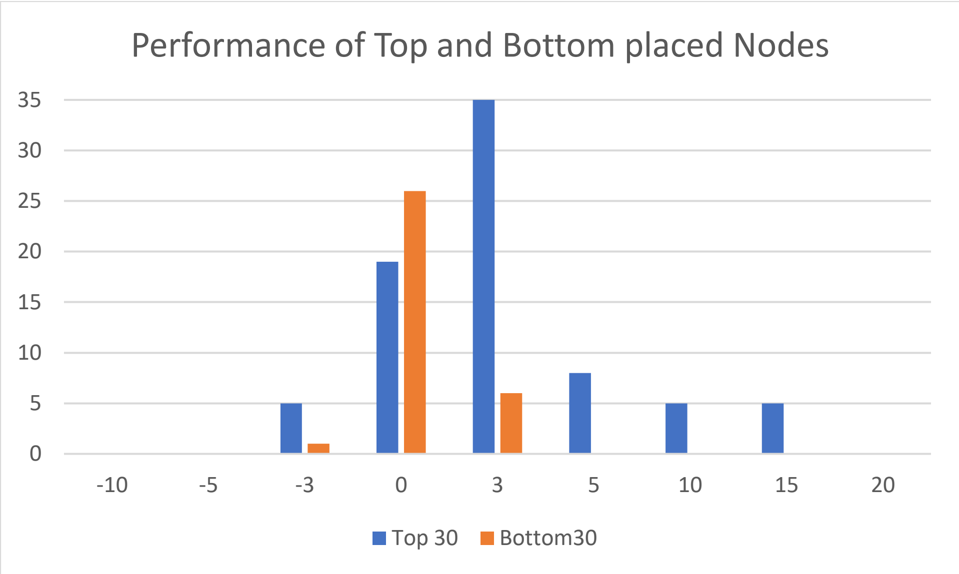



*Figure 12 Performance of top and bottom placed 30 nodes on team performances*

Table 21 highlights the statistical significance of the research findings, pointing towards a positive association between improvement in team performance and movement of high metric value nodes.

*Table 27 Statistical test for performance impact of highly connected nodes*

| z-Test: Two Sample for Means | Top 30 Nodes | Bottom 30 Nodes |
|---|---|---|
| Mean | 1.513 | -0.492 |
| Known Variance | 13.450 | 1.544 |
| Observations | 77 | 33 |

| | |
|---|---|
| Hypothesized Mean Difference | 0 |
| z | 4.262 |
| P(Z<=z) one-tail | 1.01289E-05 |
| z Critical one-tail | 1.645 |
| P(Z<=z) two-tail | 2.02579E-05 |
| z Critical two-tail | 1.960 |

Most of the bottom placed nodes are drivers. These lower ranked driver nodes only spent a few seasons in each team before leaving the network. This led the author to analyse the difference between technical and engineering members of a team with its drivers (with considerably higher degree than the bottom place nodes.) Social network analysis highlights the effect of a team's engineering employees and drivers. Comparing drivers' effect on team performance with that of other members of the team who worked in an engineering or design capacity, highlights how technical staff, compared to drivers, have more influence on the team performance. This corresponds to the case study findings.

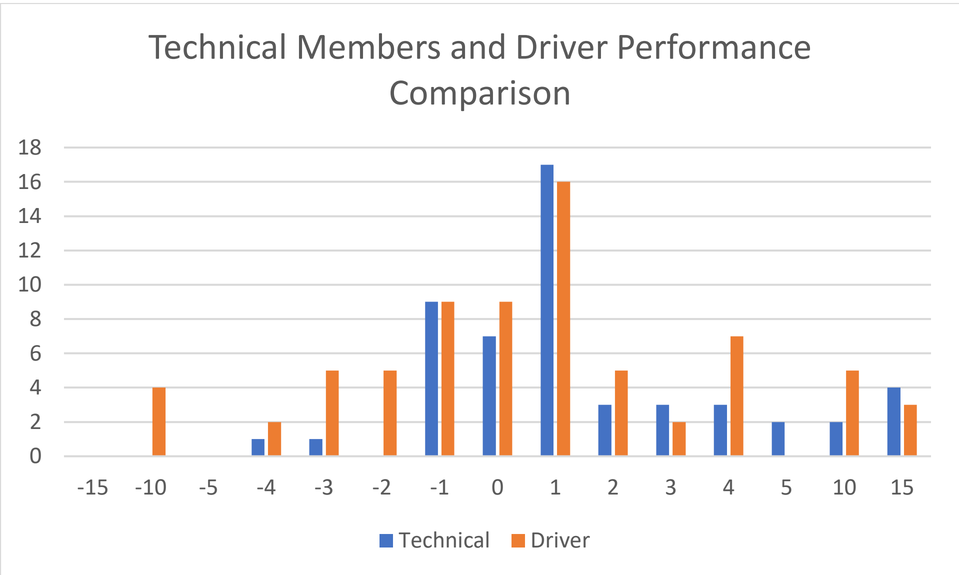



Figure 13 Effect of technical members and drivers on team performance

These differences are statistically significant as shown in the following table.

*Table 28 Statistical significance test for impact of nodes in technical roles*

| | | |
|---|---|---|
| z-Test: Two Sample for Means | | |
| | Technical | Driver |
| Mean | 1.426 | 0.168 |

| | | |
|---|---|---|
| Known Variance | 12.89 | 19.91 |
| Observations | 52 | 72 |
| Hypothesized Mean Difference | 0 | |
| z | 1.737 | |
| P(Z<=z) one-tail | 0.0412 | |
| z Critical one-tail | 1.645 | |
| P(Z<=z) two-tail | 0.0824 | |
| z Critical two-tail | 1.96 | |

The analysis in table 26 and table 27 establishes the following,

- Networked individuals improved organisational performance in an inter-organisational network.
- Among networked individuals, those individuals who are in technical and managerial capacity affect organisational performance to a greater degree than others.

These conclusions highlight the central role of individuals with high tacit knowledge content in improving organisational performance within inter-organisational networks and challenge the existing consensus on relation based and organisational ecology view of organisations and sources of their competitive advantage. The next chapter discusses these research findings in the context of interviews and case studies.

# Chapter 7. Discussion of Research Findings

The following sections lay out research findings and their main implications. This study proposes a novel method to track movement of tacit knowledge within inter-organisational network and highlights the idiosyncratic nature of Formula 1 industry, the unique time constraints facing Formula 1 teams, the connection between individuals and knowledge transfer, interactions between the teams and automotive sector and other technology companies, and the influence of individuals on team performance. The following subsections discuss the key findings.

## 7.1. Movement of Individuals, Tacit Knowledge, and Competitive Advantage

In the context of Formula 1, knowledge transfer, and more specifically tacit knowledge is of central importance. Aversa et al. (2015) and Jenkins (2010) highlight the unique the business model of Formula 1 which involves trading and selling both technology and human resource with the competitors and reflects the important role played by individuals, conduits of tacit knowledge in this process. This study shows that this movement can be tracked using social network analysis.

The mapping of movement of individuals, and tacit knowledge inherent within them, facilitates a rich analysis. The movement of individuals; those with high degrees, within the inter-organisational network; has a positive effect on team performance. These nodes, such as Adrian Newey and Ross Brawn have a positive effect and improve team's performance.

A high degree value implies that the node has more connections than other nodes in the network. These connections are associated with the movement of individuals among teams. While it can be observed from these figures that movement of high degree nodes have a positive effect on team's performance and lower degree nodes lead to negative or no net effect on team's performance, these observations are subjected to statistical test to make them more robust. This result provides quantitative support for associating tacit knowledge transfer with having a positive effect on the team performance. Identifying the bridges or gatekeepers in the network (Burt, 2005; Mishra et al., 2017; Granovetter, 2005) is crucial for understanding nodes facilitating non-redundant knowledge flows within the network.

The following table lists a few high metric value nodes who are key for team performance, as highlighted in case studies and interviews.

*Table 29 High metric value nodes and corresponding case studies and interview findings*

| Nodes | Social network analysis metrics | Case studies and interviews |
|---|---|---|
| Ross Brawn | Degree: 274<br>Betweenness centrality: 5606<br>Eigenvector centrality: 0.86 | Brawn was technical director for Ferrari 1997 – 2006, a period in which the team won 6 world championships. Brawn founded GP for 2009 season after Honda left the sport, and won constructor's championship the same year. |
| Adrian Newey | Degree: 250<br>Betweenness centrality: 7640<br>Eigenvector centrality: 0.504 | Adrian Newey designed cars have won seven world championships between 1992-2010, and are considered most aerodynamically efficient cars in Formula 1. |
| Michael Schumacher | Degree: 294<br>Betweenness Centrality: 5060<br>Eigenvector Centrality: 0.957 | Michael Schumacher was instrumental in bringing Ross Brawn and Rory Byrne to Ferrari from Benetton. Schumacher won five world championships with Ferrari, and Ferrari won six constructor championships in that period. |
| Rory Byrne | Degree: 300<br>Betweenness Centrality: 3528<br>Eigenvector Centrality: 1 | Byrne designed world championship wining cars at Benetton and Ferrari, and won seven constructor championships with those teams. |
| Ron Dennis | Degree: 278<br>Betweenness Centrality:3375<br>Eigenvector Centrality: 0.404 | Ron Dennis was team principal (and CEO) of McLaren from 1981 to 2009. McLaren won seven constructor championships, and ten drivers' championships in his tenure. He was also responsible for McLaren's engine deal with Mercedes Illmor. |
| Frank Williams | Degree: 270<br>Betweenness Centrality: 5032<br>Eigenvector Centrality: 0.376 | Frank Williams is the founder and team principal of Williams, and was responsible for highly successful collaboration with Renault between 1992 and 1997. Williams has won nine constructor championships and seven drivers' championships. |

These nodes with high degree also have moderately high betweeness centrality and eigenvector centrality values, which is not always the case in real networks. For instance, Brawn has eigenvector centrality of 0.86 and betweenenss centrality of 5606. Both these metrics reflect the node's importance within the network. High eigenvector centrality value implies that Brawn is connected to other nodes which are considered important in the network. Brawn's high betweeness centrality value reflects his favoured position in the network to the extent that he is on the links between other pairs of people in the network. This implies that more people are depended on Brawn to make connections with other people, making his influence stronger compared to other nodes. This trend, high values for betweeness, and eigenvector centrality, can be observed for all top 30 nodes (based on their degrees).

Nodes with high betweenness centrality, such as Brawn play the role of lead user in the network (Kratzer et al., 2015) High betweenness centrality is an effective indicator of an individual's '*lead user'* status. Lead users, in context of a social network, are defined as nodes with needs that cannot be met by existing solutions (von Hippel, 1986; Franke and Shah, 2003; von Hippel, 2007; Kratzer et al, 2015). Lead users are innovative members of an organisation who seek collaboration and assistance of others because the challenges facing them exceed their capabilities. These users seek feedback from their peers, help them to advance and improve their own ideas (Frank and Shah, 2003). It is important to note that these users are centrally embedded among their peer and well positioned to take advantage of their knowledge (Fleming, 2007). For a lead user, his/her peer provide input for ideas in the development phase of a new product, and such an innovative approach requires access to tacit knowledge which can only be exchange through direct contract (Polyani, 1966, 12967; Nonaka, 1994).

Studies have shown that lead users are able to take knowledge from a different domain and apply it to their context to come up with innovative solutions (Tietz et al., 2005; Lettl et al., 2006; Riggs and von Hippel, 1994; Luthje et al., 2005). This behaviour is consistent with the pattern of innovation requiring a novel (re)combination of diverse knowledge domains (Schumpeter, 1939; Usher, 1954; Nelson and Winter, 1982; Cummings and Teng, 2003; Squire et al., 2009). Gilsing et al. (2008) have established in their study of networks in pharmaceutical, chemical and automotive industries that there exists a positive relationship between innovation and betweenness centrality. This highlights the central role played by nodes with high betweenness centrality such as Ross Brawn and Michael Schumacher in driving innovation within the Formula 1 network.

When Schumacher moved to Ferrari from Benetton in 1996, he was followed by Benetton's chief designer, Rory Byrne, and technical director, Ross Brawn (table 28). All three nodes have high degree, betweenness centrality, and eigenvector centrality values in the network model. Schumacher, Brawn, and Byrne have been part of the Benetton team that won two consecutive drivers' and constructors world championship. Over the next few seasons with Ferrari, Brawn and Byrne designed and built five world championship winning cars. They also transformed the engineering capabilities of Ferrari (Brawn and Parr; 2014.)

Similarly, Adrian Newey's designs at Williams, and then at McLaren resulted in the teams winning five world championships between them. Adrian Newey had a similar effect on Red Bull Racing later. His design innovations in aerodynamics, such as reconfiguring diffuser in Williams 17B and designing blown diffuser with customised engine mapping from Renault have been some of the key sources of Williams' and Red Bull's technical advantage over other teams and led to those teams winning six world championships between them (in the period under consideration.)

This study demonstrates how the process of knowledge transfer is facilitated by connections between people in collaborating organisations, such as collaboration between Lotus and Cosworth on the DFV engine (Uzzi and Spiro, 2005; Chen, 2004; Lyles and Gundegran, 2006.) A history of past alliances can also have a positive effect on the transfer process if the technology being delivered is appropriate (Lyles and Gundegran, 2006.) The relationship between Colin Chapman and Keith Duckworth, who had worked for Chapman at Lotus, was foundational for the success of the project. But prior alliances can also be a hindrance to the knowledge transfer process when their core competencies can result in alliance partner having a better performing car (Lyles, 1998, Quintas et al., 1997; Ahuja, 2000.) Partners are protective of their core competencies and only share technologies that they have already incorporated in their cars and in process of developing and improving it. Duckworth's reluctance to share the technical know-how behind barrel turbulence is one such instance of partners protecting core competencies. The ability of partners to absorb knowledge being transferred is also a challenge and depends on resources, personal and financial (Tsai, 2001; Lichtenthaler and Lichtenthaler, 2010; Squire et al., 2009.) As pointed by interviewee one, the network of organisations is dependent on the movement of people to gain knowledge, capabilities, and process (Chen, 2004; Reagans and McEvily, 2003; Phelps et al., 2012.)

The relationships between people in this network is a source of technical advantage and since teams are working under time constraints to produce a complex engineering prototype, they always need to be able to be in a position to access this knowledge and capability pool in the network. The interviewees pointed out how this is also source of one of the more idiosyncratic character of Formula 1, which is the lack of intellectual property rights. Teams start working on cars for next season half way through the current season and consequently, are always under a process of constant development and innovation. This does not allow for the time required to file intellectual property claims and patents (Aversa et al., 2015; Aversa and Berinato, 2017.)

Teams also want to maintain their source of competitive advantage, and filing a patent application will involve disclosing not only the technology but also how it is applied by the team. Mercedes' use of beryllium allowed McLaren MP4-13 to produce more power than the Ferrari engine due to inherent elasticity of beryllium allowing for longer stokes despite revving at the same rate. McLaren and Mercedes managed to keep this source of technical advantage secret for a season before other teams and FIA found out. If McLaren and Mercedes were to patent the technology or file application for IP rights, their source of advantage would have been disclosed and allowed other teams to exploit it as well.

Another example would be Newey (table 23) changing gear arrangement for the gearbox of Williams FW17B to hide the change in position of diffuser. This allowed FW17B better grip in corners and was present in Williams FW18 and FW19 cars which ended up winning the world championship. Similarly, Duckworth kept the concept of barrel turbulence and continuously refused to share how he had accomplished it in FVA and DFV engines.

Another recent instance of this practice is the refusal of Ferrari and Mercedes to provide engines to Red Bull Racing. Red Bull Racing has been struggling with their engine manufacturer, Renault's performance since reintroduction of 1.6l V6 turbocharged engines in 2014. In this scenario, Mercedes and Ferrari engines, central to their core competencies, would have complimented Red Bull Racing's aerodynamic capabilities. This could have resulted in a better car than what Mercedes and Ferrari would been able to manufacture. Formula 1 teams are willing to enter into an alliance but not if that leads to their alliance partner and competitor having a better car.

The aversion to patents and IP rights make role of individuals in Formula 1 network that much more important. Hiring members of world championship winning teams is considered a key for bringing critical technologies and according to interviewees, more importantly, for their know-how and tacit knowledge (Chen, 2004; Nelson and Winter, 1995; McEvily et al., 2004; Palacios-Marques et al., 2013.) These individuals carry the knowledge within themselves and their hiring is an efficient way to encourage innovation and technological development. This is one of the factors influencing Formula 1 teams' high interfirm mobility.

Movement of individuals, especially those in managerial positions such as technical directors and chief designers, is an important factor in teams' success. Most individuals in managerial positions in Formula 1 also work in a technical capacity, such as technical director and team principal. These individuals in managerial positions, such as team principal, technical director, and chief engineer, are also involved in day to day operations in their administrative as well as technical capacity. They play this role on both the factory floor and grand prix circuit. An example of this will be Ross Brawn, who at Ferrari was not only responsible for the technical aspects of building a grand prix car but also played a key role in developing Ferrari's vehicle dynamics facilities and expanding their research and development capabilities. Successful Formula 1 team principals, such as Colin Chapman, Frank Williams, and Ron Dennis are often responsible for technical as well as administrative management of the car, and derive their success, in parts from their ability to achieve synergy between their administrative and technical goals (Aversa et al., 2015).

This study has highlighted how the movement of networked individuals, gatekeepers with high tacit knowledge content lead to improved organisational performance. This is the primary research finding of this study and contribution to knowledge. When these individuals, such as Ross Brawn or Adrian Newey, move from one team (organisation) to another, they not only bring their technical expertise and tacit knowledge about the car (product) but also their network which allows them to access expertise and tacit knowledge residing in other individuals within the network. Using social network analysis, this study has codified such movements and visualised the relationship between improvement in organisational performance and movement of networked individuals with high tacit knowledge content.

Therefore; the research findings challenge the central thesis of resource based (and relational view) of organisations' competitive advantage, that a pair or network of firms can develop relationships that result in sustained competitive advantage (Dyer and Singh, 1998; 675).

*Table 30 Different views of competitive advantage (adapted from Dyer and Singh, 1998; 674)*

| Dimensions | Industry Structure View | Resource Based View | Relational View | Individual-based view (this study) |
|---|---|---|---|---|
| Unit of analysis | Industry | Firm | Pair or network of firms | Individuals |
| Primary source of supernatural profits | Relative bargaining power | Physical resources (raw material, land etc.), human resources (managerial talent), technological resources (process technology etc.), intangible resources (such as reputation) | Relation specific investment, interfirm knowledge sharing routines, complementary resource endowments, and effective governance | Networked individuals with high tacit knowledge content |
| Mechanism that preserve profits | Industry barriers to entry, government regulations, production economies/sunk cost | Firm level barriers to imitation, resource scarcity, casual ambiguity, time compression, asset stock. | Dyadic/network barrier to imitation, casual ambiguity, time compression diseconomies, inter-organisational asset stock, partner scarce, resource indivisibility, institutional environment | Tacitness of the source of competitive advantage, that is the knowledge and expertise residing within networked individuals. |
| Ownership of resources | Collective | Individual firm | Collective with trading partners | Individual |

Table 29 illustrates how this study challenges, and distinguishes itself from resource based, and relational view of the firm by identifying individuals and the tacit knowledge within them as source of competitive advantage and improvement in organisational performance.

The research findings also challenge the organisational ecology view of inter-organisational networks. The organisational ecology view is centred on competition and constraints of resources. This study demonstrates how gatekeepers can alter competition and organisation's resource constraints within inter-organisational network by bringing in novel knowledge necessary for innovation and performance improvement.

## 7.2. Nature of Formula 1

Formula 1 faces a pace of the technological development and logistical challenges like businesses such as information management systems, pharmaceutical industries, and aerospace manufacturers where firms form alliances with their competitors to tackle specific projects, expand their resource base, and overcome regulatory change. Smith et al. (2007) identify these as ideal conditions for fostering knowledge transfer.

Formula 1 cars are essentially an *alliance* between the team, engine manufacturer, electronic system provider, brake manufacturers, fuel supplier, and sponsors. In this alliance, role of the constructor is that of a system integrator (Wright and Matthews, 2001.) For instance, in the case of the DFV engine, it came about because of an alliance between Lotus, Cosworth, and Ford where Ford provided corporate sponsorship for the project, Cosworth provided technical expertise and engineering in building the engine, and Lotus acted as a system integrator. This alliance is focused on 'winning races' and that is the only measure of performance (Jenkins, 2010; Jenkins and Tallman, 2015; Aversa et al., 2015, Aversa and Berinato, 2017)

The primary motivation for formation of such alliances within Formula 1 is acquiring capabilities and resources that the team lacks (Argote and Ingram, 2000; Deeds, 2003; Gupta and Govindarajan, 2000; Schulze, 2001; Cummings and Teng, 2003; Schulze et al., 2014; Pinch et al., 2003; Jenkins, 2010.) These alliances are primarily driven by 'knowledge', knowledge that can help a team win races (Argote and Ingram, 2002; Winter, 1995; Szulanski, 1996; Lyles and Gudergan, 2006; Gomes-Casseres, 2006; Dyer and Singh, 1998.) This explains why Formula 1 teams can change their longstanding relationships with engine manufacturers or tyre suppliers or any other alliance partner if they are not performing in grands prix. Other external factors such as corporate alignment and complementary competencies do play a role but gaining knowledge and technologies necessary for winning grands prix remains the prime motivator for these alliances. This can be observed in case of Renault's alliance with Red Bull Racing and the Newey designed exhaust blow diffusers for RB6.

Interviewees cite examples of collaborations in Formula 1, such as Lotus and Cosworth, Mercedes and McLaren, and Red Bull Racing and Renault. Such alliances facilitate cost saving and also provide access to otherwise difficult to reach knowledge (Szulanski, 2000; Cummings and Teng, 2003; Inkpen, 2008.) Alliance and knowledge sharing are also dependent on the partner's ability to innovate (Inkpen, 2008; Salk, 1996, Hardy et al., 2003; Lichtenthaler and Lichtenthaler, 2010.) Companies do not get into an alliance if their partner can "*out-innovate*" them in performance, they look for complementary competencies. Red Bull is known for their capabilities in the area of aerodynamics and chassis manufacturing, and combining those with the complementary competencies of Renault's engine manufacturing is advantageous for both alliance partners.

Research collaboration also plays a role in encouraging alliance formation and knowledge sharing. Interviewees highlighted how Formula 1 act as a research laboratory for automotive manufacturers (Aversa et al., 2015; Aversa and Berinato, 2017; Foxall and Johnston, 1991; Jenkins and Floyd, 2001.) However, interviewee three argued that technology being used in Formula 1 is not suitable for road cars and cross-over between racing and road car technology is non-existent and has been the case since early 1990s. This stands in contrast to Renault's participation in Formula 1 in 1970s to promote turbochargers in their road cars (Jenkins, 2010.) Before the 1990s, the technological advances in racing still had relevance for the road cars.

Formula 1 cars are result of integration of the technological know-how of the alliance partners thus system integration is critical for success of the team. This type of tacit knowledge is critical for building the car and its performance especially considering how Formula 1 cars are essentially a prototype. How external capabilities, financial resources, and personal are integrated into the process of building a car influences success or failure of the team. Teams are dependent on factors such as knowledge, people, and relationships coming together and having compatible capabilities. Formula 1, as a business, is more similar in nature to technology firms like Apple or Google, video game developers, and defence manufacturers than automotive manufacturers.

## 7.3. Formula 1: A Small World Network

Small world networks have been shown to exist in a range of field, from neural networks to creative collaborations in film industry (Newman, 2001; Newman, 2003; Schnettler, 2009). The ubiquity of small world networks has led researchers to speculate that small world networks are fundamental to how biological, social, and physical networks organise themselves for success.

Research has shown that small world networks do have an impact on performance (Uzzi and Spiro, 2005) though the positive effect only lasts up to a threshold beyond which either it has no or negative effect on the performance. Focusing on small world coefficient Q (*equation 1*), research has established that as small world coefficient Q increases, the constituent clusters of small world become more connected through nodes who either have worked together in past or are connected through a past collaboration with another node. This has implications for tacit knowledge within an organisation. A small value of Q will imply that knowledge will remain in separate organisations that make up the network and the few inter-organisational links that do exist in such a network are not made up of repeat ties or first-hand ties making it difficult to transfer novel knowledge. At the medium level of small world coefficient Q, connectivity between team rises as does cohesion within the network. These ties are either repeated links and have many common third-party relationships that facilitate dispersion of novel knowledge and creativity in the network.

The Formula 1 network presents such a scenario. The small world coefficient Q of the Formula 1 network is 13.974, which is much larger than 1 indicating the small world behaviour of the network. Table 29 highlights the other real world small world networks. It can also be noted from the table 29, that small world coefficient of Formula 1 network is close to the median of small world Q of real-world networks but when compared to a network such as one in Verspagen and Duysters (2004) study into strategic technology alliances, Q for Formula 1 network appears small. In this regard, Grannovetter (1973) have argued in their study that innovation and small world Q share an inverted U relationship. This means that a very large small world coefficient has negative implications for innovation within the network as that implies a tightly connected network with either no or very small path lengths, thus reducing the possibility of introduction of novel knowledge through nodes on the periphery.

The small world nature of Formula 1 network will imply unusually large information flowing within the network through links between nodes who have either worked together in past or connected to each other through another actor (Uzzi and Spiro, 2015; Mishra et al., 2017). This supports findings of interviews and case studies that tacit knowledge transfer facilitate via individuals. The novel knowledge is introduced in the network via these individuals and then dispersed through the whole network and constituent clusters. Small world networks also have implications for state of innovation (Uzzi and Spiro, 2005; Burt, 2004; Steen et al., 2011).

Research has shown that innovation arises from connections between disparate groups in a network (Burt, 2004; Gay and Dousset, 2005; cown et al., 2007; Steen et al., 2011), and high value of small world coefficient Q implies that such connections exist either through nodes who have worked together or with have a connection through a third actor. This small world phenomenon highlights how innovation (Gilsing et al., 2008) thrives in Formula 1 teams and responsible for their ability to respond to regulation changes ( Jenkins, 2010; Aversa, 2017).

*Table 31 Small world networks in real life (adopted from Uzzi et al., 2007; 80)*

| **Authors** | **Network** | **Period** | **Q** |
|---|---|---|---|
| **Moody (2004)** | Sociologists co-authorship | 1963-1999 | 0.72 |
| | | | |
| | | 1989-1999 | 0.63 |
| **Baum et al. (2003)** | Canadian banks | 1952-1957 | 1.21 |
| | | | |
| | | 1969-1974 | 5.9 |
| | | | |
| | | 1985-1990 | 10.78 |
| **Schilling and Phelps (2007)** | US alliances in 11 2-digit SIC codes | 1992-200 | 2.71 |
| **Davis et al. (2003)** | US Corporations interlocks | 1982 | 5.27 |

| | | | |
|---|---|---|---|
| | | | |
| | | 1999 | 4.54 |
| **Flemming et al. (2007)** | US patenting inventors | 1986-1990 | 6.8 |
| **Watts (1999)** | Power grids | | 10.61 |
| **Median Q** | | | 10.61 |
| **Mishra (2017)** | Formula 1 Network | 1992 - 2010 | 13.974 |
| **Kogut and Walker (2001)** | German firms | 1993-1997 | 20.38 |
| **Davis et al. (2003)** | US Director interlocks | 1982 | 65.48 |
| | | | |
| | | 1990 | 65.84 |
| | | | |
| | | 1999 | 68.14 |
| **Kogut and Walker (2001)** | German corporation ownership | 1993-1997 | 87.91 |
| **Verspagen and Duyster (2004)** | Strategic alliances | 1980-1996 | 531.25 |
| **Watts (1999)** | Hollywood Film Nodes | 1898-1997 | 2396.85 |

### *7.3.1 Fast clockspeed and small world network of Formula 1*

Formula 1 cars are essentially a prototype (Aversa et al., 2015; Aversa and Berinato, 2017; Foxall and Johnston, 1991; Jenkins and Floyd, 2001; Jenkins, 2010). This prototype is continuously evolved over the season and incremental innovations are necessary to maintain competitive advantage over other teams. This process happens while simultaneously team is developing next year's race car, which could be, due to regulation changes, considerably different, technologically, compared to the present car.

Formula 1 teams need to continuously evolve their product and process technologies to maintain their competitive advantage. Scholars (Fines, 1998; Williams, 1994; Mendelson and Pillai, 1999; Nadkarni and Narayana, 2007; Souza et al., 2004) have identified this need for firms to keep pace with the increasing velocity of change or *clockspeed* to survive and remain competitive as one of the key challenges for modern industries.

To keep up with the fast clockspeed, industries frequently introduce incrementally new products with progressively shortening development time and time between redesigns (Holt, 2002; Mendelson and Pillai, 1999; Souza et al., 2007). Formula 1 teams work within a set of regulations that do not allow a complete product redesign; i.e. a redesigned race car is not allowed halfway through a season. Therefore, Formula 1 teams have adopted principles of lean production (Womack et al., 2003; 2007) and focus on continuous evolution and improvement of various components, improving reliability, and integrated product and process design while working on designs and improvements for the next season.

In this fast clockspeed environment, teams rely on movement of individuals to introduce novel knowledge and facilitate innovation. This is where small world network structure of Formula 1 allows teams to exploit access to large knowledge flows via movement of individuals within the network and innovate to maintain their competitive advantage.

### 7.4. Way of Doing Things

Another theme that emerges from interviews and case analysis is the importance of processes and ways of doing things. Processes and ways of doing things is more important than the technology itself. For instance, as highlighted by interviewee one, Formula 1 teams have been using 3-D printing to test scale models in the wind tunnel since early 1990s. This ability to take an existing technology and incorporate it in existing processes to improve efficiency lies at the core of how Formula 1 teams operate. For instance, Ferrari encountered this issue when they found their engineers struggling to build John Barnard's car designs for 1995 season. When Rory Byrne and Ross Brawn joined Ferrari, they focused on improving engineering capabilities as well as building a resource pool of engineers (Brawn and Parr, 2014) They also invested in building vehicle dynamic facilities and research and development group to capture the tacit knowledge within the group. A critical factor for success of knowledge transfer is research and development. Teams investing in research are not only able to innovate but also gain from knowledge of their partners.

The importance of processes also stands out in the Renault case in late 1978 where Francois Castaing and Bernard Dudot used the CH series of engines from sportscar racing to develop the 1.5l V6 turbocharged engine for the Renault RS01. It is also evident in Duckworth's experience of working with Ford engines which he adapted for the F2 in form of FVA engine. FVA engine's distinguishing feature, the barrel turbulence, helped him design and build the 3.0L V8 DFV engine which was envisioned to use FVA piston head technology from its inception.

Exhaust blown diffusers were not new to Formula 1 and were introduced in Renault RE40 in 1983 by Jean-Claude Migeot and most teams either use the technology in 2010 or had used it in past. What was new in Newey's design was how the vertical window in the diffusers allowed it to be blown both over and under by the exhaust. *This helped the airflow going up the outside shoulder of the upper diffuser deck and the high speed exhaust gas will drive more flow through the diffuser to increase downforce.* This in itself would not have allowed for any substantial advantage over other teams, but Newey worked closely with Renault to change engine mapping for off throttle overrun. Practice off throttle overrun forces fuel through the engine even when the throttle pedal is not depressed and resulting in exhaust cases being blown. This type of engine mapping is quite common in rallying cars to prevent or minimise the turbo lag, and Renault had a history of participation in rally car championships. This allowed Renault to bring their prior experience in engine mapping and compliment Newey's exhaust blown diffuser design resulting in greater downforce and thus higher cornering speed. One of the factors behind Red Bull Racing's success was their ability to integrate Renault's engines in every aspect of their car designs and performance expectations. Red Bull made sure their development and innovation activities accounted for the role of engine manufacturer. This practice of complimentary competency and system integration can be also observed in Lotus 49 which was designed around the Cosworth DFV engine.

## 7.5. Regulations and Geographical Proximity

Regulations play a critical role in affecting knowledge transfer (Jenkins, 2010.) Having the right individual to respond to regulation changes is important for a team's success. The network of people driving knowledge sharing is contextualised by the competition and technological evolution as well as regulation. Regulation change can alter the balance of competition, and change the trajectory of technological evolution. Regulatory changes can also cause disruption.

Ross Brawn's role at Brawn GP, and later at Mercedes AMG is an instance where having the right individual to respond to the regulation change was key for team's performance. Brawn was one of the key figures behind hybrid engine technology development at Mercedes in 2010 and 2011. This early investment in the technology paid off when FIA changed the regulation and mandated use of 1.6L turbo hybrid engines with energy recovery systems for 2014 season. Similarly, collaboration between Lotus and Cosworth was result of FIA changing regulations for engine capacity from 1.5 litre to 3.0 litre. The then Lotus engine partner, Coventry Climax decided not to produce the higher capacity engine and it forced Chapman to collaborate with Cosworth, resulting in the most successful Formula 1 engine ever produced, the DFV engine.

Formula 1 teams are driven by past collaboration and geographical colocation (Jenkins and Tallman, 2015; Jenkins and Tallman, 2010.) Geographical location plays an important role in ability of a Formula 1 team to be able to exploit resources. Most Formula 1 teams are concentrated in what is known as motorsport valley in England. This area not only has teams' manufacturing and research and development facilities but also an established supply chain and various universities to guarantee materials, technology, and human resources needed for perhaps most technical sport in the world. Similarly, Italy has its own motorsport valley centred on Maranello with Ferrari and Toro Rosso, as well as Moto GP firms such as Ducati.

The success of knowledge transfer process is based on the nature of the alliance. Intra-industry alliances, such as that between Cosworth and Lotus and McLaren and Mercedes, are judged on the parameter of grands prix wins whereas inter-industry alliances, such that between McLaren and GSK, have different measurements of success.

# Chapter 8. Conclusion and Limitations

This research contributes to knowledge by proposing a novel method of tracking tacit knowledge transfer in inter-organisational networks. Tacit knowledge is difficult to codify and transfer (Polanayi, 1965; 1967) and scholars have argued that critical organisation knowledge is often tacit (Arthur et al., 1995; Boisot, 1998, Nonaka and Takechi, 1995). This is important in context of inter-organisational networks of alliances, as firms form alliances to access novel knowledge for competitive advantage (Cumming and Teng, 2003; Lyles and Gudergan, 2006; Dyer and Singh, 1998). Therefore, understanding the tacit knowledge transfer in inter-organisational networks is important not only from a knowledge management perspective but also from, an organisational performance perspective.

This research proposes the use of social network analysis to track movement of individuals in inter-organisational networks (Formula 1) and assigns ametric value to each individual within the said network. By tracking movement of individuals, and the tacit knowledge inherent in them, this methodology allows for measurement of the impact of the movement of individuals on organisation's performance. Individuals with higher impact share certain mathematical traits, such as high degree centrality and betweenness centrality value, and therefore can be compared against individuals with little or no impact on the organisation's performance. This allows for statistical comparison between the two sets of individuals and enhances the validity of the proposed methodology by providing a self-validation mechanism. A social network analysis of individuals within the inter-organisational network also facilitates identification of roles that have greater effect on team performance compared to others. These findings are reinforced by qualitative analysis in form of interviews and case studies.

The study has also identified an unusual structure of management in Formula 1 teams. Teams have a management structure which allows team principals, technical directors, and other senior managerial staff to work simultaneously on administrative as well as technical level in the factory and grand prix circuits with rest of the team. Team principals in Formula 1 often play many roles, such as chief executive and chief technical officer and are key for team's performance.

Team principals are responsible for tightly knitted team structure which allows teams to respond to external factors such as regulation changes and improvement in competitors' performance by aligning their managerial and technical resources without going through a series of managerial positions. This type of organisational structure is highly unusual for any multi-national organisation (Morschett et al., 2015).

## 8.1. Effect of Movement of Tacit Knowledge on Organisation Performance

Research findings highlight the critical role played by knowledge in inter-organisational networks. Gaining access to novel knowledge which can provide a competitive advantage is core motivation behind alliance formation within networks (Argote and Ingram, 2000; Deeds, 2003; Gupta and Govindarajan, 2000; Schulze, 2001; Cummings and Teng, 2003; Schulze et al., 2014). This study shows that tacit knowledge transfer is critical for the specific context of Formula 1 because of the nature of the industry. Formula 1 teams do not file patent applications or register their intellectual property because that would involve disclosing the source of their competitive advantage and instead rely on the individuals within the organisation to have the (tacit) knowledge and know-how of processes to gain advantage over others. Therefore; as highlighted by interviewees; teams are often looking to employ individuals from world championship winning teams, so that they can exploit their tacit knowledge of processes and way of doing things (Chen, 2004; Nelson and Winter, 1995; McEvily et al., 2004; Palacios-Marques et al., 2013) These inter-organisational networks rely on individuals to respond to externalities, such as industry or in case of Formula 1, FIA sporting regulations.

This tacit knowledge can be accessed through individuals who move from one organisation to another within an inter-organisational network (Cummings and Teng, 2003; Inkpen, 2008.) The tacit knowledge transfer takes place through individuals involved in research and development. These research collaborations between firms in an inter-organisational network facilitate the process of knowledge transfer (Uzzi and Spiro, 2005; Luthje et al., 2005; Squire et al., 2009) This exchange of knowledge between individuals is encouraged by a history of constructive past alliances between their respective organisations (Lyles and Gundegran, 2006).

These individuals carry the (tacit) knowledge which is a key for organisations' competitive advantage (Argote and Ingram, 2002; Winter, 1995; Szulanski, 1996; Lyles and Gudergan, 2006; Gomes-Casseres, 2006; Dyer and Singh, 1998.) This study has shown that movement of individuals with high level of connectedness (degree centrality) and betweemmess centrality has a positive effect on competitive performance whereas movement of individuals with lower levels of connectedness tends to have no or negative effect on organisation's performance.

Analysis also highlights a qualitative difference between categories of nodes in the network. Individuals who are working in a technical capacity, such as race engineers, designers, and technical directors have more influence on the team performance than the drivers. This was again corroborated by statistical significance test and case studies and interview analysis. The analysis highlighted the importance of individuals in senior technical positions in world championship winning teams, such as Ross Brawn and Adrian Newey whose movement to another team leads to a greater positive influence on team performance than compared to individuals in the role of drivers. This conclusion is context specific to Formula 1 teams. Nonetheless, it highlights how individuals in certain roles can affect inter-organisational network to a greater degree than others.

The movement of individuals, and tacit knowledge within them encourages innovation. Ability to innovate plays a key part in intra and inter-organisational relationships (Lictenthaler and Lichtenthaler, 2010; Tietz et al., 2005; Lettl et al., 2006; Riggs and von Hippel, 1994; Luthje et al., 2005; Squire et al., 2009). This study also demonstrates that firms in an inter-organisational network do not want to be out innovated by their partners so they protect their core competencies.

## 8.2. Small World Network of Formula 1

The network of Formula 1 teams is a small world knowledge network which has favourable implications for knowledge transfer (Verspage and Duysters, 2004; Uzzi and Spiro, 2005.) These networks have high clustering and short distance between any randomly selected pair of nodes. This implies that Formula 1 network has large knowledge flows, primarily through nodes who have either worked with each other or have another actor in common. These knowledge flows through individuals, especially those nodes who are on the periphery of the network have a positive effect on the state of innovation (Uzzi and Spiro, 2005; Burt, 2004; Schnettler, 2009; Steen et al., 2011).

The small world network structure and accompanying large knowledge flows facilitate innovation in the Formula 1 network structure allowing teams to maintain their competitive advantage in this fast-clockspeed industry. Unlike other fast-clockspeed industries, such as semi-conductors, Formula 1 teams cannot completely redesign their product in middle of a season, i.e. the race car, so they rely on incremental improvements and innovation to continuously improve the product and maintain their competitive advantages.

### 8.3. Movement of Tacit Knowledge in Inter-organisational Network

Social network analysis is a sociological tool relying on mathematic and statistics to understand social interactions among organisations, and individuals. In the case of Formula 1, application of social network analysis and various metrics present a dense inter-organisational network full of clusters and short path lengths facilitating knowledge flow. The Formula 1 network is an unusually dense and highly interconnected with small diameter for a real life network (Albert and Barabasi, 2002; Hanneman and Riddle, 2005; Newman, 2001, 2003; Uzzi, 1998; Watts and Strogatz, 1998; Uzzi and Spiro, 2005). It is also full of clusters which are essentially individual teams, which is to be expected as movement of individuals centrs around certain key nodes who are central to a team, such as Ron Dennis and Frank Williams.

These clusters at their centre have certain nodes or nodes with high values for metrics such as degree centrality and betweenness centrality (Albert and Barabasi, 2002; Hanneman and Riddle, 2005; Newman, 2003) These centrality measures give an indication of importance of these nodes in determining knowledge exchange and access within intra-organisational and inter-organisational networks (Freeman, 1977; Freeman, 1984;  von Hippel, 1986; Franke and Shah, 2003; von Hippel, 2007; ; Gilsing et al., 2008; Kratzer et al, 2015) Social network analysis also highlights the positive co-relation between movement of these nodes and the performance of teams.  Statistical analysis of these nodes, compared to lower ranked nodes, supports the conclusion that there is a link between movement of these individuals and team performance. These findings are also supported by the qualitative analysis of interviews and case studies.

### 8.4. Regulations

Researchers (Porter, 1991; Ambec et al., 2011) have argued that well-designed regulations can enhance competitiveness and innovation. This study illustrates that regulations can effectively alter the trajectory of technological evolution and competition (Jenkins, 2010). Regulatory changes also force Formula 1 teams to respond quickly to changes that affect their core competencies, such as engine capacity, fuel efficiency, and electronic driving aids. Regulatory changes can also break alliances, as observed in case of Lotus and Coventry Climax.

Formula 1 teams respond to these regulatory changes through innovation and technological improvements. These are often accomplished by either forming alliances or movement of individuals with requisite expertise to respond to these changes. Regulations are a key external factor that motivates alliance formation and movement of individuals to access relevant knowledge and know-how in Formula 1.

This study has demonstrated a novel way of analysing tacit knowledge transfer in inter-organisational networks. It identifies the effect of network position of an individual, who is conduit of tacit knowledge transfer (Deeds, 2003; Gupta and Govindarajan, 2000; Pfeffer and Sutton, 2000) on team performance. This study has also shown how different category of nodes influence the team performance to different extent.

Using the context of Formula 1, this study has demonstrated the suitability of social network analysis, a sociology-graph theory based methodology to trace and identify movement and high metric value individuals within the inter-organisational network.  The use of metrics gives mathematical structure to the analysis. The analysis has identified the small world network structure of Formula 1 network. The small world structure of Formula 1 facilitates knowledge flow and innovation within the network by introducing novel knowledge through nodes on the periphery.

For industry, this analysis highlights the positive effect of movement of networked individuals on a firm's performance. This is particularly relevant for industries that share Formula 1's technological and competitive context such as pharmaceutical, aerospace, and information management. This research shows that in an industry like Formula 1, performance is positively affected by movement of highly networked individuals among competitors

### 8.4. Implications for teaching and research, and motor sport policy

This study provides a framework for analysing tacit knowledge transfer in inter-organisational networks and in doing so offers a pedagogical tool to examine knowledge transfer process and other variables involved. By highlighting role of individuals in improving organisational performance, this study challenges researcher in the field of knowledge management, strategy, and organisational networks to explore individuals as unit of analysis. This study has not explored the implications of patents within the context of movement of tacit knowledge via individuals in inter-organisational networks and that represents a future avenue for any researcher in the field.

In terms of motor sport policy, this study has highlighted how critical networked individuals can improve organisational performance and in some cases, such as Luca Badoer, these individuals are not the most obvious. The research findings suggest that organisations within the motor sport industry and regulators would benefit from reassessing their policy with individuals as one of the key pillars of their planning. In today's environmentally conscious world where government regulators are increasingly demanding more stringent standards, individuals with expertise and high tacit knowledge content can prove important for developing new solutions and improving organisational performance.

## 8.5. Limitations and Future Work

As with any other study, this research was done within boundary conditions. Inter-organisational network structures are dependent on their empirical settings (Ahuja, 2000; Provan et al., 2007; Rowley et al., 2000). This presents challenges to generalisability of social network studies, and whether learning from one study done in a particular empirical setting can offer lessons for another context. Empirical setting encompasses the industrial setting as well as cultural setting. Scholars have studied how national cultures influence and give rise to different network practices (Cook et al., 2005; Hofstede, 2001). Such differences based on empirical settings make it difficult to extrapolate learnings from one context to another. This does not invalidate findings of social network analysis in a particular industry. It still offers the methodological and certain broader lessons about movement of individuals and the accompanying tacit knowledge that are applicable to other industries.

Access to novel knowledge is an important source of competitive advantage (Argote and Ingram, 2002; Winter, 1995; Szulanski, 1996; Lyles and Gudergan, 2006; Gomes-Casseres, 2006; Dyer and Singh, 1998; Dyer and Singh, 1998; Cummings and Teng, 2003, Chen, 2003; Ahuja, 2000) but it is not the only source from which firms' draw their competitive advantage. In specific context of Formula 1, financial resources also play a critical role in teams' ability to be competitive and win grands prix.  It is not uncommon for Formula 1 teams to withdraw from the sport because of financial regularities despite availability of human resources.

In certain cases, such as Ferrari between 1996-2006, many highly connected nodes, such as Ross Brawn, Rory Byrne, Michael Schumacher, and Jean Todt were involved in the team. In such cases, these individuals have a cumulative effect on team's performance which is greater than their individual contribution over that period. Based on the research findings of this study, gathering these highly connected nodes together would have a greater positive effect on team's performance than any single node in its individual capacity. However, this needs further research to establish a clear causal link as there are other factors that influence organisational performance.

This study has been focused on individual level and inter-organisational level of analysis and highlights the impact of individuals within the inter-organisational network. There are many other factors that will affect performance of a firm such as financial resources at a team's disposal, geographical location, patent portfolio, and regulations. In addition, an individual's impact may take some time to become apparent (perhaps even after the individual has left the firm). Formula 1 teams also have different cultural practices, and that affects individual performance.

This suggeststhat future work should focus on analysis at the firm level to understand the effect of cumulative metric value of all members of the team and other contextual factors such as regulations, technology available, cultural practices, geographical location, patent portfolio, and suppliers' performance. Particularly, social network analysis can be used to explore the effect of existing patent portfolio and its role as the source of competitive advantage in inter-organisational networks.

Future work can explore the generalisability of research findings by applying the proposed methodology to the case of Formula E. Formula E is a FIA sanctioned electronic single seater racing championship. Formula E is a relatively new FIA category but already has manufacturers such as Audi, BMW, Jaguar, Porsche, Renault, Mercedes AMG, and Mahindra participating in the world championship. Being an electric racing series, the knowledge generated within the series is of relevance for automotive manufacturers, especially advancements made in battery and electric motor technologies.

# Appendix 1 Python Syntax

```
#!/usr/bin/env python
# -*- coding: utf-8 -*-

fi = 'Input.csv'
fo = 'Output.csv'

def main():
    constructor = list()
    nodes = list()
    cyear = ''
    fr = open(fi, 'r')
    for i, line in enumerate(fr.xreadlines()):
        if i > 0:
            iline = line.strip().split(',')
            print iline
            if len(iline) == 2 and iline[0].strip() != '':
                if len(iline) == 2 and iline[1].strip() == '':
                    # Constructor
                    print 'constructor'
                    print iline[0]
                    constructor.append(iline[0].strip())
                    nodes.append([])
                if len(iline) == 2 and iline[1].strip() != '':
                    # nodes
                    print iline[0]
                    nodes[len(constructor)                                    -
1].append(iline[0].strip())
                    cyear = iline[1].strip()

    print constructor
    print nodes
```

```
fw = open(fo, 'w')
for c, constructor in enumerate(constructor):
    print constructor
    fw.write(','.join((constructor, '\r\n')))
    for n, i in enumerate(nodes[c]):
        for l in xrange(n + 1, len(nodes[c])):
            print i, ', ', nodes[c][l], ', ', cyear
            fw.write(','.join((i, nodes[c][l], cyear, '\r\n')))
```

# Appendix 2 Performance of top thirty nodes

| | Year Joined | Year Left (left after finishing the season | | Net Effect |
|---|---|---|---|---|
| **Mike Gascoyne** | | | | |
| | | | | |
| Sauber | **1992** | **1993** | 2 | 1 |
| Team Performance | 0 | 2.8 | 2.8 | |
| | | | | |
| Tyrrell | **1994** | **1997** | 4 | |
| Team Performance | 3.1 | 0.4 | -2.7 | -0.675 |
| | | | | |
| Jordan | **1998** | **2000** | 3 | |
| Team Performance | 8.18 | 3.94 | -4.24 | -1.4133333 |
| | | | | |
| Benetton/Renault | **2001** | **2003** | 3 | |
| Team Performance | 2.26 | 14.1 | 11.84 | 3.94666667 |
| | | | | |
| Toyota | **2004** | **2006** | 3 | |
| Team Performance | 1.3 | 5 | 3.7 | 1.23333333 |
| | | | | |
| | | | | |
| **Andrew Alsworth** | | | | |
| | | | | |
| Benetton | **1992** | **1998** | 7 | |
| Team Performance | 21.87 | 7.93 | -13.94 | -1.9914286 |
| | | | | |
| BAR | **1999** | **2005** | 7 | |
| Team Performance | 0 | 11.92 | 11.92 | 1.70285714 |
| | | | | |
| Honda/Brawn | **2006** | **2009** | 4 | |
| Team Performance | 5.15 | 26.73 | 21.58 | 5.395 |
| | | | | |
| | | | | |
| **Alan Permane** | | | | |
| Benetton | **1992** | **2001** | 10 | |
| Team Performance | 21.87 | 2.26 | -19.61 | -1.961 |
| | | | | |
| Renault | **2002** | **2008** | 7 | |
| Team Performance | 5.2 | 11.4 | 6.2 | 0.88571429 |
| | | | | |
| | | | | |
| **Steve Nielsen** | | | | |

| | | | | |
|---|---|---|---|---|
| Tyrrell | **1992** | **1997** | 6 | |
| Team Performance | 1.44 | 0.4 | -1.04 | -0.1733333 |
| | | | | |
| Benetton | **2000** | **2001** | 2 | |
| Team Performance | 4.62 | 2.26 | -2.36 | -1.18 |
| | | | | |
| Renault | **2002** | **2009** | 8 | |
| Team Performance | 5.2 | 5.36 | 0.16 | 0.02 |
| | | | | |
| | | | | |
| **Luigi Mazzola** | | | | |
| Ferrari | **1992** | **2010** | 19 | |
| Team Performance | **5.14** | **20.63** | 15.49 | 0.81526316 |
| | | | | |
| | | | | |
| **Dickie Stanford** | | | | |
| Williams | 1992 | 2010 | 19 | |
| Team Performance | 39.42 | 3.56 | -35.86 | -1.8873684 |
| | | | | |
| **Mattia Binotto** | | | | |
| Ferrari | 1995 | 2010 | 16 | |
| Team Performance | 17.1 | 20.63 | 3.53 | 0.220625 |
| | | | | |
| | | | | |
| **Jock Clear** | | | | |
| Williams | **1995** | **1998** | 4 | |
| Team Performance | 26.3 | 9.13 | -17.17 | -4.2925 |
| | | | | |
| BAR | **1999** | **2005** | 7 | |
| Team Performance | 0 | 5.15 | 5.15 | 0.73571429 |
| | | | | |
| Honda/Brawn | **2006** | **2009** | 4 | |
| Team Performance | 12.25 | 26.73 | 14.48 | 3.62 |
| | | | | |
| Mercedes | **2010** | | 1 | |
| Team Performance | 11.15 | | 11.15 | 11.15 |
| | | | | |
| | | | | |
| **Pat Symonds** | | | | |
| Benetton | **1992** | **2001** | 10 | |
| Team Performance | 21.87 | 2.26 | -19.61 | -1.961 |
| | | | | |

| | | | | |
|---|---|---|---|---|
| Renault | **2002** | **2010** | 9 | |
| Team Performance | 5.2 | 8.5 | 3.3 | 0.36666667 |
| | | | | |
| | | | | |
| **Rory Byrne** | | | | |
| Benetton | **1992** | **1996** | 5 | |
| Team Performance | 21.87 | 16.35 | -5.52 | -1.104 |
| | | | | |
| Ferrari | **1997** | **2007** | 11 | |
| Team Performance | 23.78 | 45.84 | 22.06 | 2.00545455 |
| | | | | |
| | | | | |
| **Adrian Newey** | | | | |
| Williams | **1992** | **1996** | 5 | |
| Team Performance | 39.42 | 42.07 | 2.65 | 0.53 |
| | | | | |
| McLaren | **1997** | **2005** | 9 | |
| Team Performance | 14.25 | 24.66 | 10.41 | 1.15666667 |
| | | | | |
| Red Bull | **2006** | **2010** | 5 | |
| Team Performance | 2.28 | 25.92 | 23.64 | 4.728 |
| | | | | |
| | | | | |
| **Ron Dennis** | | | | |
| McLaren | **1992** | **2010** | 19 | |
| Team Performance | 23.8 | 23.66 | -0.14 | -0.0073684 |
| | | | | |
| | | | | |
| **Neil Oatley** | | | | |
| McLaren | **1992** | **2010** | 19 | |
| Team Performance | 23.8 | 23.66 | -0.14 | -0.0073684 |
| | | | | |
| | | | | |
| **Rubens Barrichello** | | | | |
| Jordan | **1993** | **1996** | 4 | |
| Team Performance | 0.2 | 5.29 | 5.09 | 1.2725 |
| | | | | |
| Stewart | **1997** | **1999** | 3 | |
| Team Performance | 1.35 | 8.65 | 7.3 | 2.43333333 |
| | | | | |
| Ferrari | **2000** | **2005** | 6 | |
| Team Performance | 39.35 | 13.55 | -25.8 | -4.3 |

| | | | | |
|---|---|---|---|---|
| | | | | |
| Honda/Brawn | **2006** | **2009** | 4 | |
| Team Performance | 12.25 | 26.73 | 14.48 | 3.62 |
| | | | | |
| Williams | **2010** | | 1 | |
| Team Performance | 3.56 | | 3.56 | 3.56 |
| | | | | |
| | | | | |
| **Ross Brawn** | | | | |
| Benetton | **1992** | **1996** | 5 | |
| Team Performance | 21.87 | 16.35 | -5.52 | -1.104 |
| | | | | |
| Ferrari | **1997** | **2006** | 10 | |
| Team Performance | 23.78 | 28.63 | 4.85 | 0.485 |
| | | | | |
| Honda B | **2007** | **2009** | 3 | |
| Team Performance | 1.35 | 26.73 | 25.38 | 8.46 |
| | | | | |
| Mercedes | **2010** | | 1 | |
| Team Performance | 11.15 | | 11.15 | 11.15 |
| | | | | |
| | | | | |
| **Jean Todt** | | | | |
| Ferrari | **1994** | **2007** | 14 | |
| Team Performance | 17.67 | 45.84 | 11.15 | 0.79642857 |
| | | | | |
| | | | | |
| **Luca Di Montezemolo** | | | | |
| Ferrari | **1992** | **2010** | 19 | 0.8205263 |
| Team Performance | 5.04 | 20.63 | 15.53 | |
| | | | | |
| | | | | |
| **Flavio Briatore** | | | | |
| Benetton | 21.87 | 2.26 | -19.61 | |
| Team Performance | | | | |
| | **2002** | **2008** | 7 | |
| Renault | 5.4 | 11.4 | 6 | 0.85 |
| Team Performance | | | | |
| | | | | |
| **Michael Schumacher** | | | | |
| Benetton | **1992** | **1995** | 4 | 2.5725 |
| Team Performance | 21.87 | 32.16 | 10.29 | |

| | | | | |
|---|---|---|---|---|
| **Ferrari** | **1996** | **2006** | 11 | 1.072 |
| Team Performance | 16.83 | 28.63 | 11.8 | |
| | | | | |
| **Mercedes** | **2010** | | 1 | 11.15 |
| Team Performance | 11.15 | | 11.15 | |
| | | | | |
| | | | | |
| **Luca Badoer** | | | | |
| Scuderia Italia | **1993** | | | |
| Team Performance | | | | |
| | | | | |
| Minardi | **1995** | | 1 | 1 |
| Team Performance | 1 | | 1 | |
| | | | | |
| Forti | **1996** | | | |
| Team Performance | | | | |
| | | | | |
| Minardi | **1999** | | 1 | 1 |
| Team Performance | 1 | | 1 | |
| | | | | |
| Ferrari | **2009** | | 1 | 9.97 |
| Team Performance | 9.97 | | 9.97 | |
| | | | | |
| | | | | |
| **Frank Williams** | | | | |
| Williams | 1992 | 2010 | 19 | -1.887 |
| Team Performance | 39.42 | 3.56 | -35.86 | |
| | | | | |
| | | | | |
| **Stefano Domenicali** | | | | |
| Ferrari | **1995** | **2010** | 16 | 0.218 |
| Team Performance | 17.14 | 20.63 | 3.49 | |
| | | | | |
| | | | | |
| **Tim Densham** | | | | |
| Tyrrell | **1992** | **1998** | | |
| Team Performance | 0 | 0 | | |
| | | | | |
| Benetton | **1999** | **2001** | 3 | -0.53 |
| Team Performance | 3.85 | 2.26 | -1.59 | |
| | | | | |

| | | | | |
|---|---|---|---|---|
| Renault | **2002** | **2010** | 9 | 0.366 |
| Team Performance | 5.2 | 8.5 | 3.3 | |
| | | | | |
| | | | | |
| **Giancarlo Fisichella** | | | | |
| Jordan | **1997** | | 1 | 7.47 |
| Team Performance | 7.47 | | 7.47 | |
| | | | | |
| Benetton | **1998** | **2001** | 4 | -1.4175 |
| Team Performance | 7.93 | 2.26 | -5.67 | |
| | | | | |
| Renault | **2005** | **2007** | 3 | -4.806 |
| Team Performance | 25.88 | 11.46 | -14.42 | |
| | | | | |
| Force India | **2008** | | | |
| Team Performance | 0 | | | |
| | | | | |
| Ferrari | **2009** | **2010** | 2 | 5.33 |
| Team Performance | 9.97 | 20.63 | 10.66 | |
| | | | | |
| | | | | |
| **Mark Smith** | | | | |
| Jordan | **1992** | **2000** | 9 | 0.415 |
| Team Performance | 0.2 | 3.94 | 3.74 | |
| | | | | |
| Benetton | **2001** | | 1 | 2.26 |
| Team Performance | 2.26 | | 2.26 | |
| | | | | |
| Renault | **2002** | **2004** | 3 | 3.25 |
| Team Performance | 5.2 | 14.96 | 9.76 | |
| | | | | |
| Jordan | **2005** | | | |
| Team Performance | 1.69 | | | |
| | | | | |
| Red Bull | **2005** | **2008** | 4 | -0.12 |
| Team Performance | 4.61 | 4.13 | -0.48 | |
| | | | | |
| Force India | **2009** | **2010** | 2 | 0.75 |
| Team Performance | 2 | 3.5 | 1.5 | |
| | | | | |
| | | | | |
| **Patrick Head** | | | | |

| | | | | |
|---|---|---|---|---|
| Williams | **1992** | **2010** | 19 | -1.887 |
| Team Performance | 39.42 | 3.56 | -35.86 | |
| | | | | |
| | | | | |
| **Ron Meadows** | | | | |
| BAR | **2001** | **2005** | 5 | 0.26 |
| Team Performance | 3.85 | 5.15 | 1.3 | |
| | | | | |
| Honda | **2006** | **2009** | 3 | 4.823 |
| Team Performance | 12.25 | 26.73 | 14.48 | |
| | | | | |
| Mercedes | **2010** | | 1 | |
| Team Performance | 11.15 | | 11.15 | 11.15 |
| | | | | |
| | | | | |
| **Jarno Trulli** | | | | |
| Minardi | **1997** | | | |
| Team Performance | | | | |
| | | | | |
| Prost | **1997** | **1999** | 3 | 0.7 |
| Team Performance | 0 | 2.1 | 2.1 | |
| | | | | |
| Jordan | **2000** | **2001** | 2 | 0.18 |
| Team Performance | 3.94 | 4.3 | 0.36 | |
| | | | | |
| Renault | **2002** | **2004** | 3 | 3.25 |
| Team Performance | 5.2 | 14.96 | 9.76 | |
| | | | | |
| Toyota | **2004** | **2009** | 6 | 1.32 |
| Team Performance | 1.3 | 9.25 | 7.95 | |
| | | | | |
| Lotus | **2010** | | | |
| Team Performance | | | | |
| | | | | |
| | | | | |
| **Craig Wilson** | | | | |
| Tyrrell | **1997** | | 1 | 0.4 |
| Team Performance | 0.4 | | 0.4 | |
| | | | | |
| Williams | **1998** | **2002** | 5 | 2.336 |
| Team Performance | 9.13 | 20.81 | 11.68 | |
| | | | | |

| | | | | |
|---|---|---|---|---|
| BAR | **2003** | **2005** | 3 | 0.32 |
| Team Performance | 4.17 | 5.15 | 0.98 | |
| | | | | |
| Honda | **2006** | **2008** | 3 | -3.3 |
| Team Performance | 12.25 | 2 | -10.25 | |
| | | | | |
| Mercedes | **2010** | | 1 | |
| Team Performance | 11.15 | | 11.15 | 11.15 |
| | | | | |
| | | | | |
| **Dominic Harlow** | | | | |
| Jordan | **2003** | **2005** | 3 | -0.15 |
| Team Performance | 2.08 | 1.63 | -0.45 | |
| | | | | |
| Spyker | **2006** | **2007** | | |
| Team Performance | 0 | 0 | | |
| | | | | |
| Force India | **2008** | **2010** | 3 | 0.6 |
| Team Performance | 0 | 2 | 2 | |

# Appendix 3 Performance of bottom thirty nodes

| | Year Joined | Year Left (after finishing the season) | | Net Effect |
|---|---|---|---|---|
| **Taki Inoue** | | | | |
| Simtek | **1994** | | 1 | |
| Team Performance | 0 | | 0 | 0 |
| | | | | |
| Footwork | 1994 | **1995** | 1 | |
| Team Performance | 2.2 | 1.1 | -1.1 | -1.1 |
| | | | | |
| | | | | |
| **Patrick Friesacher** | | | | |
| Minardi | **2005** | | 1 | |
| Team Performance | 0.9 | | 0.8 | 0.8 |
| | | | | |
| | | | | |
| **Hideki Noda** | | | | |
| Larrousse | **1994** | | 1 | |
| Team Performance | 0.48 | | -0.24 | -0.24 |
| | | | | |
| | | | | |
| **Nicholas Wirth** | | | | |
| Simtek | **1994** | **1995** | 2 | |
| Team Performance | 0 | 0 | 0 | 0 |
| | | | | |
| Benetton | **1996** | **1999** | 4 | |
| Team Performance | 16.35 | 3.85 | -12.5 | -3.125 |
| | | | | |
| | | | | |
| **Richard Taylor** | | | | |
| Simtek | **1994** | **1995** | 2 | |
| Tea Performance | 0 | 0 | 0 | 0 |
| | | | | |
| | | | | |
| **Domenico Schiattarella** | | | | |
| Simtek | **1994** | **1995** | 2 | |
| Team Performance | 0 | 0 | 0 | 0 |
| | | | | |
| | | | | |
| **Andrea Chiesa** | | | | |
| Fondmental | **1992** | | 1 | |
| Team Performance | | 0 | 0 | 0 |
| | | | | |
| | | | | |

| | | | | |
|---|---|---|---|---|
| **Ray Boulter** | | | | |
| Tyrrell | 1991 | **1992** | 1 | |
| Team Performance | 3 | 1.44 | -1.56 | -1.56 |
| | | | | |
| | | | | |
| **Denis Nursey** | | | | |
| Tyrrell | 1991 | **1992** | 1 | |
| Team Performance | 3 | 1.44 | -1.56 | -1.56 |
| | | | | |
| | | | | |
| **John Creak** | | | | |
| Footwork | 1994 | **1995** | 1 | |
| Team Performance | 2.2 | 1.1 | -1.1 | -1.1 |
| | | | | |
| | | | | |
| **Eric Van De Poele** | | | | |
| Brabham | 1991 | **1992** | 1 | |
| Team Performance | 0.7 | 0 | -0.7 | -0.7 |
| | | | | |
| | | | | |
| **Trevor Sheumack** | | | | |
| Fondmental | 1991 | **1992** | 1 | |
| Team Performance | 0 | 0 | 0 | 0 |
| | | | | |
| | | | | |
| **Erik Bernard** | | | | |
| Lotus | 1993 | **1994** | 1 | |
| Team Performance | 2.9 | 0 | -2.9 | -2.9 |
| | | | | |
| | | | | |
| **Jean-Pierce Chatenet** | | | | |
| Lotus | 1993 | **1994** | 1 | |
| Team Performance | 2.9 | 0 | -2.9 | -2.9 |
| | | | | |
| | | | | |
| **Peter Wyss** | | | | |
| Fondmental | 1991 | **1992** | 1 | |
| Team Performance | 0 | 0 | 0 | 0 |
| | | | | |
| | | | | |
| **Robert Dassaud** | | | | |
| Ligier | 1991 | **1992** | 1 | |
| Team Performance | 0 | 1.4 | 1.4 | 1.4 |
| | | | | |
| | | | | |

| | | | | |
|---|---|---|---|---|
| **Michel Tifu** | | | | |
| Larrousse | 1991 | **1992** | 1 | |
| Team Performance | 0.4 | 0.24 | -0.16 | -0.16 |
| | | | | |
| | | | | |
| **Glanfranco Palazzoli** | | | | |
| Fondmetal | 1991 | **1992** | 1 | |
| Team Performance | | 0 | 0 | 0 |
| | | | | |
| | | | | |
| **Eric Guilloud** | | | | |
| Larrousse | 1991 | **1992** | 1 | |
| Team Performance | 0.4 | 0.24 | -0.16 | -0.16 |
| | | | | |
| | | | | |
| **Eric Vullemin** | | | | |
| Lotus | 1993 | **1994** | 1 | |
| Team Performance | 2.9 | 0 | -2.9 | -2.9 |
| | | | | |
| **Jean-Pierre Paoli** | | | | |
| Ligier | 1991 | **1992** | 1 | |
| Team Performance | 0 | 1.4 | 1.4 | 1.4 |
| | | | | |
| | | | | |
| **Darry Hindenoch** | | | | |
| Lotus | 1993 | **1994** | 1 | |
| Team Performance | 2.9 | 0 | -2.9 | -2.9 |
| | | | | |
| | | | | |
| **Shinji Nakano** | | | | |
| Prost | 1996 | **1997** | | |
| Team Performance | 0 | 0 | | 0 |
| | | | | |
| | | | | |
| **Gordon Coppuck** | | | | |
| March F1 | 1991 | **1992** | 1 | |
| Team Performance | | 0.7 | 0.7 | 0.7 |
| | | | | |
| | | | | |
| **Dave Luckett** | | | | |
| March F1 | 1991 | **1992** | 1 | |
| Team Performance | | 0.7 | 0.7 | 0.7 |
| | | | | |
| | | | | |
| **Tino Holloway** | | | | |

| | | | | |
|---|---|---|---|---|
| Larrousse | 1991 | **1992** | 1 | |
| Team Performance | 0.4 | 0.24 | -0.16 | -0.16 |
| | | | | |
| | | | | |
| **Philippe Alliot** | | | | |
| Larrousse | 1991 | **1992** | 1 | |
| Team Performance | 0.4 | 0.24 | -0.16 | -0.16 |
| | | | | |
| | | | | |
| **Henny Vollenberg** | | | | |
| Larrousse | 1991 | **1992** | 1 | |
| Team Performance | 0.4 | 0.24 | -0.16 | -0.16 |
| | | | | |
| | | | | |
| **Brendan Gribben** | | | | |
| Larrousse | 1991 | **1992** | 1 | |
| Team Performance | 0.4 | 0.24 | -0.16 | -0.16 |
| | | | | |
| | | | | |
| **Jerry Bond** | | | | |
| March F1 | 1991 | **1992** | 1 | |
| Team Performance | | 0.7 | 0.7 | 0.7 |
| | | | | |
| | | | | |
| **Carlo Gancia** | | | | |
| Forti | | **1995** | 1 | |
| Team Performance | | 0 | 0 | 0 |

# Appendix 4 Performance of top thirty nodes in technical roles

| | Year Joined | Year left (after finishing the season) | | Net Effect |
|---|---|---|---|---|
| **Mike Gascoyne** | | | | |
| Sauber | **1992** | **1993** | 2 | |
| Team Performance | 0 | 2.8 | 2.8 | 1.4 |
| | | | | |
| Tyrrell | **1994** | **1997** | 4 | |
| Team Performance | 3.1 | 0.4 | -2.7 | -0.675 |
| | | | | |
| Jordan | **1998** | **2000** | 3 | |
| Team Performance | 8.18 | 3.94 | -4.24 | -1.41333 |
| | | | | |
| Benetton/Renault | **2001** | **2003** | 3 | |
| Team Performance | 2.26 | 14.1 | 11.84 | 3.946667 |
| | | | | |
| Toyota | **2004** | **2006** | 3 | |
| Team Performance | 1.3 | 5 | 3.7 | 1.233333 |
| | | | | |
| | | | | |
| **Andrew Alsworth** | | | | |
| Benetton | **1992** | **1998** | 7 | |
| Team Performance | 21.87 | 7.93 | -13.94 | -1.99143 |
| | | | | |
| BAR | **1999** | **2005** | 7 | |
| Team Performance | 0 | 11.92 | 11.92 | 1.702857 |
| | | | | |
| Honda/Brawn | **2006** | **2009** | 4 | |
| Team Performance | 5.15 | 26.73 | 21.58 | 5.395 |
| | | | | |
| **Alan Permane** | | | | |
| Benetton | **1992** | **2001** | 10 | |
| Team Performance | 21.87 | 2.26 | -19.61 | -1.961 |
| | | | | |
| Renault | **2002** | **2008** | 7 | |
| Team Performance | 5.2 | 11.4 | 6.2 | 0.885714 |
| | | | | |
| | | | | |
| **Steve Nielsen** | | | | |
| Tyrrell | **1992** | **1997** | 6 | |
| Team Performance | 1.44 | 0.4 | -1.04 | -0.17333 |
| | | | | |
| Benetton | **2000** | **2001** | 2 | |
| Team Performance | 4.62 | 2.26 | -2.36 | -1.18 |

| | | | | |
|---|---|---|---|---|
| Renault | **2002** | **2009** | 8 | |
| Team Performance | 5.2 | 5.36 | 0.16 | 0.02 |
| | | | | |
| **Luigi Mazzola** | | | | |
| Ferrari | **1992** | **2010** | 19 | |
| Team Performance | **5.14** | **20.63** | 15.49 | 0.815263 |
| | | | | |
| | | | | |
| **Dickie Stanford** | | | | |
| Williams | **1992** | **2010** | 19 | |
| Team Performance | 39.42 | 3.56 | -35.86 | -1.88737 |
| | | | | |
| | | | | |
| **Mattia Binotto** | | | | |
| Ferrari | **1995** | **2010** | 16 | |
| Team Performance | 17.1 | 20.63 | 3.53 | 0.220625 |
| | | | | |
| | | | | |
| **Jock Clear** | | | | |
| Williams | **1995** | **1998** | 4 | |
| Team Performance | 26.3 | 9.13 | -17.17 | -4.2925 |
| | | | | |
| BAR | **1999** | **2005** | 7 | |
| Team Performance | 0 | 5.15 | 5.15 | 0.735714 |
| | | | | |
| Honda/Brawn | **2006** | **2009** | 4 | |
| Team Performance | 12.25 | 26.73 | 14.48 | 3.62 |
| | | | | |
| Mercedes | **2010** | | 1 | |
| Team Performance | 11.15 | | 11.15 | 11.15 |
| | | | | |
| | | | | |
| **Pat Symonds** | | | | |
| Benetton | **1992** | **2001** | 10 | |
| Team Performance | 21.87 | 2.26 | -19.61 | -1.961 |
| | | | | |
| Renault | **2002** | **2010** | 9 | |
| Team Performance | 5.2 | 8.5 | 3.3 | 0.366667 |
| | | | | |
| | | | | |
| **Rory Byrne** | | | | |
| Benetton | **1992** | **1996** | 5 | |
| Team Performance | 21.87 | 16.35 | -5.52 | -1.104 |

| | | | | |
|---|---|---|---|---|
| | | | | |
| Ferrari | **1997** | **2007** | 11 | |
| Team Performance | 23.78 | 45.84 | 22.06 | 2.005455 |
| | | | | |
| | | | | |
| **Adrian Newey** | | | | |
| Williams | **1992** | **1996** | 5 | |
| Team Performance | 39.42 | 42.07 | 2.65 | 0.53 |
| | | | | |
| McLaren | **1997** | **2005** | 9 | |
| Team Performance | 14.25 | 24.66 | 10.41 | 1.156667 |
| | | | | |
| Red Bull | **2006** | **2010** | 5 | |
| Team Performance | 2.28 | 25.92 | 23.64 | 4.728 |
| | | | | |
| | | | | |
| **Ron Dennis** | | | | |
| McLaren | **1992** | **2010** | 19 | |
| Team Performance | 23.8 | 23.66 | -0.14 | -0.00737 |
| | | | | |
| | | | | |
| **Neil Oatley** | | | | |
| McLaren | **1992** | **2010** | 19 | |
| Team Performance | 23.8 | 23.66 | -0.14 | -0.00737 |
| | | | | |
| | | | | |
| **Ross Brawn** | | | | |
| Benetton | **1992** | **1996** | 5 | |
| Team Performance | 21.87 | 16.35 | -5.52 | -1.104 |
| | | | | |
| Ferrari | **1997** | **2006** | 10 | |
| Team Performance | 23.78 | 28.63 | 4.85 | 0.485 |
| | | | | |
| Honda B | **2007** | **2009** | 3 | |
| Team Performance | 1.35 | 26.73 | 25.38 | 8.46 |
| | | | | |
| Mercedes | **2010** | | 1 | |
| Team Performance | 11.15 | | 11.15 | 11.15 |
| | | | | |
| | | | | |
| **Stefano Domenicali** | | | | |
| Ferrari | **1995** | **2010** | 16 | 0.218 |
| Team Performance | 17.14 | 20.63 | 3.49 | |
| | | | | |

| | | | | |
|---|---|---|---|---|
| | | | | |
| **Tim Densham** | | | | |
| Tyrrell | **1992** | **1998** | | |
| Team Performance | 0 | 0 | | |
| | | | | |
| Benetton | **1999** | **2001** | 3 | -0.53 |
| Team Performance | 3.85 | 2.26 | -1.59 | |
| | | | | |
| Renault | **2002** | **2010** | 9 | 0.366 |
| Team Performance | 5.2 | 8.5 | 3.3 | |
| | | | | |
| | | | | |
| **Mark Smith** | | | | |
| Jordan | **1992** | **2000** | 9 | 0.415 |
| Team Performance | 0.2 | 3.94 | 3.74 | |
| | | | | |
| Benetton | **2001** | | 1 | 2.26 |
| Team Performance | 2.26 | | 2.26 | |
| | | | | |
| Renault | **2002** | **2004** | 3 | 3.25 |
| Team Performance | 5.2 | 14.96 | 9.76 | |
| | | | | |
| Jordan | **2005** | | | |
| Team Performance | 1.69 | | | |
| | | | | |
| Red Bull | **2005** | **2008** | 4 | -0.12 |
| Team Performance | 4.61 | 4.13 | -0.48 | |
| | | | | |
| Force India | **2009** | **2010** | 2 | 0.75 |
| Team Performance | 2 | 3.5 | 1.5 | |
| | | | | |
| | | | | |
| **Patrick Head** | | | | |
| Williams | **1992** | **2010** | 19 | -1.887 |
| Team Performance | 39.42 | 3.56 | -35.86 | |
| | | | | |
| | | | | |
| **Ron Meadows** | | | | |
| BAR | **2001** | **2005** | 5 | 0.26 |
| Team Performance | 3.85 | 5.15 | 1.3 | |
| | | | | |
| Honda | **2006** | **2009** | 3 | 4.823 |
| Team Performance | 12.25 | 26.73 | 14.48 | |
| | | | | |

| | | | | |
|---|---|---|---|---|
| Mercedes | **2010** | | 1 | |
| Team Performance | 11.15 | | 11.15 | 11.15 |
| | | | | |
| | | | | |
| **Craig Wilson** | | | | |
| Tyrrell | **1997** | | 1 | 0.4 |
| Team Performance | 0.4 | | 0.4 | |
| | | | | |
| Williams | **1998** | **2002** | 5 | 2.336 |
| Team Performance | 9.13 | 20.81 | 11.68 | |
| | | | | |
| BAR | **2003** | **2005** | 3 | 0.32 |
| Team Performance | 4.17 | 5.15 | 0.98 | |
| | | | | |
| Honda | **2006** | **2008** | 3 | -3.3 |
| Team Performance | 12.25 | 2 | -10.25 | |
| | | | | |
| Mercedes | **2010** | | 1 | |
| Team Performance | 11.15 | | 11.15 | 11.15 |
| | | | | |
| | | | | |
| **Dominic Harlow** | | | | |
| Jordan | **2003** | **2005** | 3 | -0.15 |
| Team Performance | 2.08 | 1.63 | -0.45 | |
| | | | | |
| Spyker | **2006** | **2007** | | |
| Team Performance | 0 | 0 | | |
| | | | | |
| Force India | **2008** | **2010** | 3 | 0.6 |
| Team Performance | 0 | 2 | 2 | |

# Appendix 5 Performance of top thirty drivers

| | Year Joined | Year Left (after finishing the season | | Net Effect |
|---|---|---|---|---|
| **Michael Schumacher** | | | | |
| Benetton | **1992** | **1995** | 4 | 2.5725 |
| Team Performance | 21.87 | 32.16 | 10.29 | |
| | | | | |
| Ferrari | **1996** | **2006** | 11 | 1.072 |
| Team Performance | 16.83 | 28.63 | 11.8 | |
| | | | | |
| Mercedes | **2010** | | 1 | 11.15 |
| Team Performance | 11.15 | | 11.15 | |
| | | | | |
| | | | | |
| **Luca Badoer** | | | | |
| Scuderia Italia | **1993** | | | |
| Team Performance | | | | |
| | | | | |
| Minardi | **1995** | | 1 | 1 |
| Team Performance | 1 | | 1 | |
| | | | | |
| Forti | **1996** | | | |
| Team Performance | | | | |
| | | | | |
| Minardi | **1999** | | 1 | 1 |
| Team Performance | 1 | | 1 | |
| | | | | |
| Ferrari | **2009** | | 1 | 9.97 |
| Team Performance | 9.97 | | 9.97 | |
| | | | | |
| | | | | |
| **Rubens Barrichello** | | | | |
| Jordan | **1993** | **1996** | 4 | |
| Team Performance | 0.2 | 5.29 | 5.09 | 1.2725 |
| | | | | |
| Stewart | **1997** | **1999** | 3 | |
| Team Performance | 1.35 | 8.65 | 7.3 | 2.433333 |
| | | | | |
| Ferrari | **2000** | **2005** | 6 | |
| Team Performance | 39.35 | 13.55 | -25.8 | -4.3 |
| | | | | |
| Honda/Brawn | **2006** | **2009** | 4 | |
| Team Performance | 12.25 | 26.73 | 14.48 | 3.62 |

| | | | | |
|---|---|---|---|---|
| Williams | **2010** | | 1 | |
| Team Performance | 3.56 | | 3.56 | 3.56 |
| | | | | |
| | | | | |
| **Giancarlo Fisichella** | | | | |
| Jordan | **1997** | | 1 | 7.47 |
| Team Performance | 7.47 | | 7.47 | |
| | | | | |
| Benetton | **1998** | **2001** | 4 | -1.4175 |
| Team Performance | 7.93 | 2.26 | -5.67 | |
| | | | | |
| Renault | **2005** | **2007** | 3 | -4.806 |
| Team Performance | 25.88 | 11.46 | -14.42 | |
| | | | | |
| Force India | **2008** | | | |
| Team Performance | 0 | | | |
| | | | | |
| Ferrari | **2009** | **2010** | 2 | 5.33 |
| Team Performance | 9.97 | 20.63 | 10.66 | |
| | | | | |
| | | | | |
| **Jarno Trulli** | | | | |
| Minardi | | **1997** | 1 | |
| Team Performance | | 0 | 0 | |
| | | | | |
| Prost | **1998** | **1999** | 2 | 0.95 |
| Team Performance | 0.2 | 2.1 | 1.9 | |
| | | | | |
| Jordan | **2000** | **2001** | 2 | 0.18 |
| Team Performance | 3.94 | 4.3 | 0.36 | |
| | | | | |
| Renault | **2002** | **2004** | 3 | 3.253333 |
| Team Performance | 5.2 | 14.96 | 9.76 | |
| | | | | |
| Toyota | **2005** | **2009** | 6 | -0.445 |
| Team Performance | 11.92 | 9.25 | -2.67 | |
| | | | | |
| Lotus | | **2010** | 1 | |
| Team Performance | | 0 | 0 | |
| | | | | |
| | | | | |
| **David Coulthard** | | | | |
| Williams | **1994** | **1995** | 2 | -1.035 |

| | | | | |
|---|---|---|---|---|
| Team Performance | 28.36 | 26.29 | -2.07 | |
| | | | | |
| McLaren | **1996** | **2004** | 9 | -0.21667 |
| Team Performance | 11.78 | 9.83 | -1.95 | |
| | | | | |
| Red Bull | **2005** | **2008** | 4 | -0.12 |
| Team Performance | 4.61 | 4.13 | -0.48 | |
| | | | | |
| | | | | |
| **Fernando Alonso** | | | | |
| Minardi | | **2001** | 1 | |
| Team Performance | | 0 | 0 | |
| | | | | |
| Renault | **2003** | **2006** | 4 | 3.8 |
| Team Performance | 14.1 | 29.3 | 15.2 | |
| | | | | |
| McLaren | | **2007** | | |
| Team Performance | | | | |
| | | | | |
| Renault | **2008** | **2009** | 2 | -3.7 |
| Team Performance | 11.4 | 4 | -7.4 | |
| | | | | |
| Ferrari | | **2010** | 1 | 10.66 |
| Team Performance | 9.97 | 20.63 | 10.66 | |
| | | | | |
| | | | | |
| **Mark Webber** | | | | |
| Minardi | | **2002** | 1 | 0.5 |
| Team Performance | | 0.5 | 0.5 | |
| | | | | |
| Jaguar | **2003** | **2004** | 2 | -0.73 |
| Team Performance | 2.88 | 1.42 | -1.46 | |
| | | | | |
| Williams | **2005** | **2006** | 2 | -3.685 |
| Team Performance | 8.94 | 1.57 | -7.37 | |
| | | | | |
| Red Bull | **2007** | **2010** | 4 | 5.14 |
| Team Performance | 5.39 | 25.95 | 20.56 | |
| | | | | |
| | | | | |
| **Jenson Button** | | | | |
| Williams | | **2000** | 1 | -0.08 |
| Team Performance | 8.41 | 8.33 | -0.08 | |
| | | | | |

| | | | | |
|---|---|---|---|---|
| Benetton | | **2001** | 1 | -2.36 |
| Team Performance | 4.62 | 2.26 | -2.36 | |
| | | | | |
| Renault | | **2002** | 1 | 5.2 |
| Team Performance | | 5.2 | 5.2 | |
| | | | | |
| BAR | **2003** | **2005** | 3 | 0.326667 |
| Team Performance | 4.17 | 5.15 | 0.98 | |
| | | | | |
| Honda/Brawn GP | **2006** | **2009** | 4 | 3.62 |
| Team Performance | 12.25 | 26.73 | 14.48 | |
| | | | | |
| McLaren | | **2010** | 1 | 12.63 |
| Team Performance | 11.03 | 23.66 | 12.63 | |
| | | | | |
| | | | | |
| **Olivier Panis** | | | | |
| Ligier | **1994** | **1996** | 3 | 0.166667 |
| Team Performance | 3.1 | 3.6 | 0.5 | |
| | | | | |
| Prost | **1997** | **1999** | 3 | 0.066667 |
| Team Performance | 0 | 0.2 | 0.2 | |
| | | | | |
| BAR | **2001** | **2002** | 2 | -1.135 |
| Team Performance | 3.85 | 1.58 | -2.27 | |
| | | | | |
| Toyota | **2003** | **2005** | 3 | 3.12 |
| Team Performance | 2.56 | 11.92 | 9.36 | |
| | | | | |
| | | | | |
| **Pedro De La Rosa** | | | | |
| Arrows | **1999** | **2000** | 2 | |
| Team Performance | 0 | 0 | 0 | |
| | | | | |
| Jaguar | **2001** | **2002** | 2 | -0.115 |
| Team Performance | 2.04 | 1.81 | -0.23 | |
| | | | | |
| McLaren | **2003** | **2009** | 7 | -1.67571 |
| Team Performance | 22.76 | 11.03 | -11.73 | |
| | | | | |
| Sauber | | **2010** | 1 | -3.3 |
| Team Performance | 5.59 | 2.29 | -3.3 | |
| | | | | |
| | | | | |

| | | | | |
|---|---|---|---|---|
| **Felipe Massa** | | | | |
| Sauber | | **2002** | 1 | -2.6 |
| Team Performance | 5 | 2.4 | -2.6 | |
| | | | | |
| Sauber | **2004** | **2005** | 2 | -1.15 |
| Team Performance | 5 | 2.7 | -2.3 | |
| | | | | |
| Ferrari | **2006** | **2010** | 5 | -1.6 |
| Team Performance | 28.63 | 20.63 | -8 | |
| | | | | |
| | | | | |
| **Nick Heidfeld** | | | | |
| Prost | | **2000** | 1 | -2.1 |
| Team Performance | 2.1 | 0 | -2.1 | |
| | | | | |
| Sauber | **2001** | **2003** | 3 | -0.66667 |
| Team Performance | 5 | 3 | -2 | |
| | | | | |
| Jordan | | **2004** | 1 | -1.38 |
| Team Performance | 2.08 | 0.7 | -1.38 | |
| | | | | |
| Williams | | **2005** | 1 | -3.59 |
| Team Performance | 12.53 | 8.94 | -3.59 | |
| | | | | |
| Sauber/BMW | **2006** | **2010** | 5 | -0.574 |
| Team Performance | 5.1 | 2.23 | -2.87 | |
| | | | | |
| | | | | |
| **Kimi Raikkonen** | | | | |
| Sauber | | **2001** | 1 | 3.7 |
| Team Performance | 1.3 | 5 | 3.7 | |
| | | | | |
| McLaren | **2002** | **2006** | 5 | 0.194 |
| Team Performance | 14.7 | 15.67 | 0.97 | |
| | | | | |
| Ferrari | **2007** | **2009** | 3 | -11.9567 |
| Team Performance | 45.84 | 9.97 | -35.87 | |
| | | | | |
| | | | | |
| **Anthony Davidson** | | | | |
| BAR | | **2002** | 1 | -2.27 |
| Team Performance | 3.85 | 1.58 | -2.27 | |
| | | | | |
| BAR | | **2005** | 1 | -11.79 |

| | | | | |
|---|---|---|---|---|
| Team Performance | 16.94 | 5.15 | -11.79 | |
| | | | | |
| Super Aguri | **2007** | **2008** | 2 | -0.445 |
| Team Performance | 0.89 | 0 | -0.89 | |
| | | | | |
| | | | | |
| **Christian Klien** | | | | |
| Jaguar | | **2004** | 1 | -1.46 |
| Team Performance | 2.88 | 1.42 | -1.46 | |
| | | | | |
| Red Bull | **2005** | **2006** | 2 | -1.165 |
| Team Performance | 4.61 | 2.28 | -2.33 | |
| | | | | |
| Honda | | **2007** | 1 | -10.9 |
| Team Performance | 12.25 | 1.35 | -10.9 | |
| | | | | |
| | | | | |
| **Mika Hakkinen** | | | | |
| Team Lotus | | **1992** | 2 | 1.2 |
| Team Performance | 0.7 | 3.1 | 2.4 | |
| | | | | |
| McLaren | **1993** | **2001** | 8 | 0.36125 |
| Team Performance | 20.19 | 23.08 | 2.89 | |
| | | | | |
| | | | | |
| **Jacques Villeneuve** | | | | |
| Williams | **1996** | **1998** | 3 | -10.98 |
| Team Performance | 42.07 | 9.13 | -32.94 | |
| | | | | |
| BAR | **1999** | **2003** | 5 | 0.834 |
| Team Performance | 0 | 4.17 | 4.17 | |
| | | | | |
| Renault | | **2004** | 1 | 0.86 |
| Team Performance | 14.1 | 14.96 | 0.86 | |
| | | | | |
| Sauber | **2005** | **2006** | 2 | 1.2 |
| Team Performance | 2.7 | 5.1 | 2.4 | |
| | | | | |
| | | | | |
| **Adrian Sutil** | | | | |
| Midland | | **2006** | 1 | |
| Team Performance | | 0 | 0 | |
| | | | | |
| Spyker | | **2007** | 1 | 0.22 |

| | | | | |
|---|---|---|---|---|
| Team Performance | | 0.22 | 0.22 | |
| | | | | |
| Force India | **2008** | **2010** | 3 | 1.166667 |
| Team Performance | 0 | 3.5 | 3.5 | |
| | | | | |
| | | | | |
| **Ralf Schumacher** | | | | |
| Jordan | **1997** | **1998** | 2 | 0.355 |
| Team Performance | 7.47 | 8.18 | 0.71 | |
| | | | | |
| Williams | **1999** | **2004** | 6 | 0.686667 |
| Team Performance | 8.41 | 12.53 | 4.12 | |
| | | | | |
| Toyota | **2005** | **2007** | 3 | -3 |
| Team Performance | 11.92 | 2.92 | -9 | |
| | | | | |
| | | | | |
| **Takuma Sato** | | | | |
| Jordan | | **2002** | 1 | -2.3 |
| Team Performance | 4.3 | 2 | -2.3 | |
| | | | | |
| BAR | **2003** | **2005** | 3 | 0.326667 |
| Team Performance | 4.17 | 5.15 | 0.98 | |
| | | | | |
| Super Aguri | **2006** | **2008** | 3 | |
| Team Performance | 0 | 0 | 0 | |

# Appendix 6 Interview Questionnaire

1. In your experience, is knowledge transfer a motivation behind strategic alliance in Formula 1?

   1.1 (If yes) what are the processes that facilitate this transfer of knowledge?

   1.2 (If no) what motivates firms to get into alliances?

2. What factors affect this process?

   2.1. Do you this industry variables of competition, evolution, and technology adequately cover the effect of industry on the knowledge transfer process?

   2.2. What other variables effect this process?

3. What role does the nature of knowledge (tacit or explicit) play in this process?

   3.1. Does the nature of knowledge affect the choices of Formula 1 team in alliances?

4. Do you think prior alliance have a bearing on this process of knowledge transfer?
5. Does the closeness of knowledge to core competencies of the source the source firm affect the process?
6. What role does a firm's absorptive capacity play in this process?
7. Are there any other dimensions that afffect the knowledge transfer process?
8. Do these factors and dimensions affect the success of knowledge transfer process?
9. Does directionality play any role in the success of knowledge transfer process?
10. What variables/dimensions/factors are critical for success of knowledge transfer process?

# Appendix 7 Interview Transcripts

## Interviewee 1

Date: 03/11/2015.

Interviewee 1 is Professor of Business Strategy at an internationally renowned British university and has been involved in Formula 1 research for two decades. His research focuses on the areas of competitive strategy and innovation. He has published extensively on motorsport, and Formula 1.

***Transcript***

**Interviewee 1:** Hi Danish.

**Author**: Hello Professor. How are you?

**Interviewee 1**: Very good?

**Interviewee 1**: How are you?

**Author:** Good as well thank you though do I do have...I am suffering from a cold so my voice might sound funny. Sorry about that.

**Interviewee 1:** No problem.

**Author:** Yes, so I wouldn't waste your time and I'd straight away get to the question. So starting with the first question. So, in your experience what would you say that is the main motivation behind the formation of strategic alliances in Formula 1?

**Interviewee 1:** Well I guess on one level to win races. That's what they're doing, a Formula 1 car is in alliance. And that's Or they will make whatever partnerships are going to allow them, help them to perform on the track. I mean we've, we're seeing a very good example of this playing out at the moment with Red Bull. Yes you know were what actually they're trying to do is to find a new alliance having found themselves in a situation where the partner isn't

sufficiently competitive. So fundamentally that that's what it's all about. It's trying to access capability, resources that they otherwise wouldn't be able to have.
**Author:** Okay. And do you think that all this ties into a knowledge transfer.

**Interviewee 1:** Yeah. Whether its knowledge transfer in the sense of knowhow going from one to the other, not necessarily because essentially what they're getting is knowledge that they don't have. So thats why you know otherwise they'd build their own power units so they need someone to do the power unit but knowledge transfer tends to go on more in the way of how you apply these different technologies so. So clearly there has to be some shared understanding of the challenges of aero dynamics for example in designing a power unit.

**Author:** Absolutely.

**Interviewee 1:** You need to be cognizant and sharing ideas. So knowledge is moving between the partners in that sense but not in the sense of a technology moving sort of all in a job from one area to another and move on.

**Author:** Okay. Yeah that makes sense. And as you've already pointed out the main motivation for this is to win races that's all that Formula 1 is about. When these collaborations happen, how do think that you know what are the processes through which you know the engine designer understands, the engine manufacturer understands the aerodynamics in more linear construction of cars.

**Interviewee 1:** So yeah I think the way it works is once a partnership is agreed at a senior level then these myriad of connections people within the organization and worked together to make things happen. So you know for example. You know every team will have a Pirelli Engineer working closely with them around the tyres, the temperatures, how much tyres are working and that person works for Pirelli but also they are dedicated on the relationship with Mercedes, Williams or whoever to make that work so it operates at all those different levels. Once it's agreed that we work together on this, they're very good, I think then getting that right the way through the organization. Even someone like Mercedes Benz H P P who provide the power units. They clearly will work with the Mercedes Benz chassis team, the main team if you like but they will also work with Williams, Lotus and with potentially Manor.

**Interviewee 1:** It's all happens next year you know so they have their customers and they will treat those customers you know perhaps not quite at the level of the works team but they will treat them very well and are just as enthusiastic about helping them with their performance as they may be with Works team.

**Author**Okay. And what factors do you see affecting this process where personal are moving around. You know they have shared goals in terms of winning races.

**Interviewee 1:** What do you mean in terms of...

**Author:** This process of exchanging information. So if Mercedes Benz is working with say Manor next year they have the contract down, so what factors would affect that process of collaboration.

**Interviewee 1:** Well the paradox is motorsport valley as a cluster. The paradox of the cost is because people move around the knowledge groups around the cluster even as people around different organizations. So people know other people and they know the people work. That's part of the cost. Those networks that you develop and build up so. So you know the fact that someone who moves from one team to another what it often means is generally although there have been one or two high profile examples as this. Generally it's not IP that is being taken in the form designs or whatever. But it's knowhow because it's people that have the knowhow so. So knowhow does get moved around does get you know when I was at Mercedes we did this and when I was at Red Bull we did this because part of people's value in the labour market is clearly if they're in a world championship team then people often look to recruit those people in the assumption that they will get some of that that competitive potential, competitive capability that they have.

**Author:** Yes. Yeah that makes complete sense. So as as part of my research. I've been mainly focusing on in terms of what you know what industry variables are affecting this process, this process of alliances. By industry variables I mean competition, how competition affect, how the technology involved affect. So potentially Williams, for Williams it'll be be very expensive and probably technologically speaking improbable to make their own engine. So they go to Mercedes and in the process of evolution, so Williams have been following a curve in terms of revolution of their technological capabilities so they are very good at making their; you know electronic management system engine management system. So I'm asking that that apart from these three variables that I am looking at do you think you know they adequately cover these three variables between them among them.

**Interviewee 1:** No I think there's another one which is regulation.

**Author:** Okay okay.

**Interviewee 1:** And regulation as you've seen with the shift to the one point six litre energy recovery system units could change the balance of competition, can change the direction of the evolution of technology. So the direct regulatory intervention is often what creates the disruption, not always you know. So for example we saw back in the 80s Renault in using the existing regulations we've said that you could have a three litre normally aspirated or one point five litre turbo, and they create a disruption by doing that in other cases the disruption was created by the rate changes in regulation.

**Author:** Okay.

**Interviewee 1:** So I think I think to me from what you you just described the regulation will change the need for alliances, different relationships. The most obvious one is with the KERS with the energy recovery systems.

**Author:** Yeah. Yeah. That makes sense. So regulation is something which I should have a look at them. Moving on. As you were mentioning you know people move around and they carry their know how with them. So that's really tacit knowledge that's what we are talking about here. So I'm just wondering how important a role, do you think does tacit knowledge plays in these alliances in this process of transferring your expertise from one team to another.

**Interviewee 1:** Well I guess there's two different things. When you say transferring from one team to another, what do you mean? Is it the knowledge going from Mercedes to Williams or do you mean the knowledge going from Williams to Mercedes high performance power trains.

**Author:** I actually mean for both those cases.

**Interviewee 1:** Yeah. Because it's an interesting one because essentially when someone takes a partner, so for example take Xtract as an example. Yes. They do a lot of gears.

**Author:** Yeah yeah.

**Interviewee 1:** I mean technology. Then Xtract absorbs tacit knowledge by working with some teams. Yeah. And then are able to apply it and working with others so. So in that sense it gets moved from the alliance partner working with a number of different teams even though as we said you know there's no IP, there's no there's no laws being breached. No confidentiality is being breached but essentially what they're doing. So like a lot of consultants, is selling know how. Industry is part of what you're buying when you buy their products.

**Author:** So it's very interesting that you've pointed out Xract because I've been in touch with them. I'm also doing a survey as part of my research. I've sent them the survey/ So do you think the knowledge that they have gained from working with these Formula 1 constructors and engine manufacturers and what not and they've tried to apply it in to the gearboxes they are trying to manufacture for road cars, production cars.

**Interviewee 1:** Well yes. Yeah. Because Xtract's model, business model was to take exactly that. To move the technology because the technology started off in Rally cross that's where the original sort of gearbox which is more like a motorcycle gearbox in terms of how how it how it works. And they took that into Formula 1. They took it into touring cars. It took in two other four wheeler. And that's exactly their business model. To take a concept and developing one area then introduce it in other forms of motorsports.

**Author:** Okay. And I would imagine that and this kind of association with you know and with Formula 1 teams in past if you have past alliances if you have a history of working with Formula 1 organization it plays into your favour when you go looking for business.

**Interviewee 1:** Yes it can do. It can do it but its technology that can deliver. Yeah. It's appropriate.

**Author:** Okay.

**Interviewee 1:** So it goes you know for example you know it may be its all aerodynamics. It may be far less important in other race series than something like a gearbox. Yes which is a lot more transferable as a technology.

**Author:** Absolutely. Yeah. The same can be said about turbos as well. So building up on this. Let's say, I mean this, this case of McLaren and Mercedes, they had a very long partnership before they parted their ways in 2014. Some would say not a very wise decision. But Honda, on part of McLaren because Honda has not been doing very well this season.

**Interviewee 1:** Yeah of course it's an interesting history to the whole thing. Yes. Going back to the Brawn…

**Author:** Yeah. So going back to that association between Mercedes and McLaren. How much do you think McLaren has benefited in terms of their production car plans because they are manufacturing their own engine. As far as I am aware the three point six or eight litre turbo that they got in their road cars.

**Interviewee 1:** I don't know the answer to that. Generally they transfer far less than we might suppose, between Formula 1 and automotive because the economics of it are totally different. So I don't know the answer to that. And you know. I'm not sure because you know the Briksworth operation clearly which was an acquisition as well like Mercedes. McLaren would know a lot of that in terms of Formula 1. How that would transfer it to roads, I'm not sure. Because the economics are totally different.

**Author:** Okay. Yeah. Yeah that makes sense because I was thinking in terms of when firms get into alliances within Formula 1. Suppose Williams is you know offering their i.t. services or engine management services the electronics expertise to another team in Formula 1. How much would they be thinking in terms of protecting their core competencies? Because this is what sort of distinguishes, makes them stand out.

**Interviewee 1:** Oh well yeah. I think they're very clear about that. The technology they're offering they would see is pretty much obsolete. Well not obsolete necessarily but because they know what they're working on in the future which is the source of advantage, the other innovative ideas so they will look to capitalize, make generate value out of technology but they will be very sure that they're not you know giving any of the crown jewels away in doing that. So for example Williams provided gearbox or was it formula three at one time and it also done deal with Manor to provide the gearbox and again for them it's a cost saving exercise for both of them. Right now it's giving Williams a bit of revenue stream, and in Manor they don't have the cost of doing it themselves. So that works. But they they wouldn't do it if they felt there was anything giving any competitive advantage away because nowadays you see gearboxes are fairly well regulated and they're like engines used to be. So they're fairly standardized, they have a fixed number. They've got set dimensions the gears have got to be made to. And so there isn't a lot of competitive advantage that can be gained in that particular area.

**Author:** So moving on from this topic to next related topic that is of absorptive capacity. So for a team like Manor Marussia, they're getting into alliance with Williams as you said they're going to supply a gearbox, Mercedes is planning to supply the engine. Because technologically Mercedes engine that they will get next year is quite well ahead of the Ferrari engine they're using from last year. How much do you think that that would affect their ability to absorb this new technology and make it work?

**Interviewee 1:** Yeah I think. It's always a problem which is why Red Bull are getting in to a bit of a very difficult situation because of course the design of the car has got to optimize the power unit and all the [power units are different. So generally work will start on the new car as soon as the existing one is launched. Yeah that really gets underway towards the middle of the season. So July August time was when they really sort of get going with it and of course the further down the line you go without knowing what how you're actually going to be designing around. It totally compromises your ability to progress the development of the car. So I think there will be different challenges in every way both in building up relationships clearly with understanding how the different organizations work that they've now got to interface with and understanding you know some of the technological characteristics that might be distinctive that they need to recognize the way they develop their car to match the power unit.

**Author:** That's very interesting. And what other dimensions, I mean we have already talked about absorptive capacity and closeness to their core competencies, prior alliances and tacit knowledge. Do you think this process of alliance and the process of knowledge transfer, does a team gain anything from this?

**Interviewee 1:** Well it's all as you say about knowledge. There is also an external facing aspect here from the one about the compatibility. The complementarities in terms of brand and market. So I think that's one of Renault's problems with Red Bull of course because Red Bull’s sponsorship is from Infinity. Nissan's luxury car brand. And which basically overshadowed sort of Renault relationship so I think there is something about this sort of market pricing in formula 1 because it is also a shop window for these organizations there is something about alignment and complementarity. I mean even if you think about Ferrari you've got this sort of colour coding of organizations you know. Ferrari and Shell, colour coding a line because of the colours of the brands. So there is there is also this external facing element to it. I think it's in there as well.

**Author:** Yeah. And now the rumour mill is churning out that Aston Martin you know might take over Force India and they will get the name. Aston Martin F1 team because owners cannot pay back the loan they got from Diagio. So this is really interesting and very helpful professor. Moving on the last part of the interview which is about the success of you know getting knowledge and transferring knowledge in these alliances. So any other factors I mean other than the variables and the dimensions that we have talked about any other factors that you think in your opinion affect this process.

**Interviewee 1:** And what is the process?

**Author:** By process I mean the alliance growing together, working together, getting technology, getting engine manufacturers, building their chasis, sticking them together, and doing the system integration and making it all work.

**Interviewee 1**Yeah I think if you think of it multileveled ie there is knowledge these relationships as people coming, all those teams coming together that those organizations come together. So I think I think as long as you're looking at those different levels then are these internal capabilities aligning. And what I'm sort of also like there is there is also an external base element to it I think. Yeah I think that that that sort of high level pretty much covers it.

**Author:** Okay. And what do you think is easier for Formula 1 to collaborate with automotive manufacturer and take some of the innovative stuff that they are working and implement it within the realm of F1 rather than automotive manufactures, I mean we were talking about

Xtract. Is it difficult for Xtract, is it difficult, more difficult for Xtract to take technology from F1 gear boxes and implement for production.

**Interviewee 1:** Yeah I think the interesting thing, the interesting anomaly about Formula 1 and more motorsport more general is generally in the prototype business. So they're in what I guess you you sometimes hear referred to as the Valley of Death. Yes. Was tween this sort of early discovery concept and manufacturing, you got this sort of concept prototype development and all that. So they are they are different very different capabilities. They have different business models and that means that actually for example if you look to motorsport often that the connections are not in automotive movement because of the scale and the costs that many needed they are actually more often in areas like aerospace, defense solution where you go looking at faster rates you're looking for more innovation you're looking for less mass production you're looking at constant development, more in those kind of industries than you often are in the automotive industry. So yes there are sort of overlaps in connections but actually in terms of compatibility of those capabilities Well actually it's more in say aerospace and defense perhaps than it is in automotive.

**Interviewee 1:** Now there is this interesting example of Honda who in their previous forays into Formula 1 famously rotate engineers all through the years. And therefore. But therefore what they're looking at is a kind of capability development. In other words they're not looking into an idea they put on the road cars and they want those engineers to be more adaptive more innovative faster be more time sensitive with how they think about here. And that's the benefit they get from sort of dipping them into the F1 process. Generally these days because it's so specialist you do see less of that. So Mercedes rather than you know building how units themselves they acquire the specialist provider and there is a little bit of you know people can get seconded and so on this looks a bit like go on but not to the same level as perhaps it was in the 80s and 90s.

**Author:** That is very helpful. So you would say tech in flow in Formula 1 so to speak, I mean there's that famous example of McLaren and Hercules aerospace working on carbon fibre chassis together. So you would think tech inflow is more from these aerospace and defense industries then automotive.

**Interviewee 1:** Well possibly but I think it's the interesting thing inflow implies that these aerospace people is promoting and seeing these opportunities. Absolutely not. F1 people are trying to solve problems to make the car go faster. Therefore they're looking wherever they can find a technology an idea that would help make the car go faster. So they're looking across the piece of software technology video gaming you know in terms of all the simulations they're looking in all these places to get ideas to help them improve their performance so it's their drive to innovate and improve this. It's making them try and find these ideas and give them an advantage so they're looking everywhere way.

**Author:** So to speak they are industry agnostic and they do not care as long as they can solve the problem.

**Interviewee 1:** Exactly. Yeah. And so they but they're going to typically look at those industries that are a more leading edge more pushing technology. And generally in automotive that's not a lot of what they're doing. So they've got to look in the software in the high tech industries they're going to look as I was saying in these sort of aerospace industries where they're sort of at the leading edge where innovation is really finding new ways of doing things.

**Interviewee 1:** I guess probably more closely in a way that people like you know like Tesla and like you know Apple and Google. Well more work should be focused and looking at some new firms. I think I think what they often do is they make use of some of their capability in areas like materials. So the automotive manufacturer and I know this what Ross said about the relationship between Fiat and Ferrari was that actually they made an effort in Ferrari to find out what capability they had in Fiat and how they could use that. One of the areas was some work they were doing on materials or new materials testing and all that kind of thing. So and so they will always look for those opportunities where they which can help them take the car that us.

**Author:** And would this go on to explain the sort of relationship for example where McLaren was in relationship with GSK for a while.

**Interviewee 1:** Yeah. Yeah exactly. Well that is GSK looking for ways to benefit because one time I think its GSK  had some consumer brands. Lucas a head and shoulders which in which they sold off. Now as I understand it the relationship is that people from the McLaren applied technologies which of course is their technology transfer business. So not a Formula 1 team. McLaren spend time are allocated so many days to help GSK deal with some of the issues and problems they try to do with it.

**Author:** Which is not necessarily linked to their F1 business.

**Interviewee 1:** No no. I mean both McLaren and William have businesses that are focused on generating revenue from F1 which are based around transfer, McLaren’s is more sort of data driven. Williams’ a bit more sort of general engineering. But that's the role of those business units. So people feel they're working in Formula 1 but they're not really because the Formula 1 team focused on Formula 1 cars and the idea of the current applied technologies Williams advanced engineering us they have a business unit that can support these other activities.

**Author:** That's very helpful. The last question is what do you think is the critical factor in this process of getting the technology or knowledge and implementing it and succeeding..

**Interviewee 1:** They are systems integrators you know they're not an expert in a particular technology. They're good at pooling and bringing in whatever technologies they need and integrating them into a race car. That's absolutely right. So so therefore they identify well with the use of this technology or we need a bit do this or let's try this out so 3D printing for example F1 teams had 3D printing in the 90s you know and now is everyone's discovering it. Yeah. it wasn't as fast or whatever it is now. But they're just searching for ways in which they can go from a design on a screen to create that model to put it in the wind tunnel to manufacturing a component. And so yeah they're always looking. And then they will always find ways. I think the biggest challenge is often cultural alignment. Because for example in defense industry is almost the cultural opposite to Formula 1. So I think that then becomes a key about how you can get this knowledge sharing working is finding that culture alignment so that these two organizations can work together. And typically you know as we've seen with someone like Mercedes you know they've done it in a more intelligent way. We saw when Ford bought Jaguar Racing or. Stewart for example you know that that they treat it as a separate business. They don't interfere with it. They don't over corporatise it. And that helps it align with its partners. The other F1 teams.

**Author:** Yes. Yeah. I think that as you pointed out is very crucial. Thank you very much professor. That was the script I had in my mind. Thank you for your time.

## Interviewee 2

Date: 10/03/2016.

Interviewee 2 is Associate Professor of Strategy based at a highly ranked British university. His research is focused on investigating the interplay of innovation, business models, and alliances on firm performance. He is considered one of the leading academic experts in the motorsport industry and his empirical fields of research are often based on Formula 1.

***Transcript**:*

**Author:** Okay I guess this is recording.

**Interviewee 2:** Okay. So number one strategic alliances knowledge transfer from no one. First question. In your experience is knowledge transfer and motivation behind strategic alliances imprinted on it. Yes it is for sure. And one of the processes that facilitates this transfers is knowledge. Well the process the processes are the fact that the companies are for example have been working for a long time so they know how each other work. I think for example long term alliances between manufacturers and engine producers. That is usually motivated by the fact that the companies are rigging each other and have some kind of routines in place. In this regard also on geographical co-location helps. So the fact that they are in the same area helps. This is for example the case why certain companies like Mercedes or Hass they still decided to move in the area where Formula one is, rather than working for example from US or why certain other cases companies like HRC SPANIA Racing did very poorly by keeping their facilities back in Spain. So these are definitely also the possibility of having people that formerly worked for the supplier and now works for example for a main team. That's a good way of creating knowledge transfer. Because they're the CEO and maybe that was not working out with Renault engine; and is now in the board of the team and so they know how to work.

**Author:** So moving on, the three factors from industry's point of view that I am looking at are competition, technology involved and then pace of evolution of technology. Interviewee 1 suggested that I should include regulation into that process because it plays a role...so what do you think about these variables and do you think they adequately cover what I'm trying to find out here about the knowledge transfer process.

**Interviewee 2:** Yeah they definitely. Very interesting very interesting aspect. I think they all play. They are all in these variables for sure competition for sure. Evolution, technological sophistication. Sure. Meaning when people enter into alliances because they think that somebody can do their job better than they do and because let's say you have a specialized brake producer like AP Racing and Brembo and they can come up with something which is more effective in a shorter time frame. Economies of scale can also help them produce more parts and so dig down the costs. The problem is that you know Formula One cars are prototypes or prototypical products. So they do very few common components. Very few parts very few models per year which means that in the end there are no economies of scale. So if another company makes millions of breaks has machinery to manufacture the right breaks. That's an advantage.

**Author:** So you think that that plays an important role in when companies like Ferrari and McLaren think about sourcing their brakes from Brembo.

**Interviewee 2:** I think there's an aspect that is related to innovation.

**Interviewee 2:** So you can access valuable innovation many times you can also access valuable innovation that has been developed by your competitors. So let’s say a producer, an engine producer has developed a very good engine who is supplying this engine to your competitors. You want to enter in relationship with them because you want to have the same engine. I mean let's look at what happened last year. Red Bull ended up with a Renault engine underperforming. So the first thing they saw is that team like Williams said an excellent engine thanks to Mercedes. So they tried to break their relationship with Renault and move to Mercedes and Mercedes of course decided not to give the engine because otherwise there with their capabilities in aerodynamics of Red Bull and engine of Mercedes, they would have been a much tougher competitor. So yes this is one of the reasons I think the main reason why companies decide to create alliances.

**Author:** So moving on the second part is about the dimensions of knowledge transfer. Basically I'm looking at tacitness, and you know tacit knowledge plays a huge role in performance, prior alliances, proximity to core competencies, and absorptive capacity. I want to take them one by one starting with tacit knowledge. In your opinion because I postulated the movement of people which really affects the performance. Because they bring tacit knowledge with them.

**Interviewee 2:** Yeah the knowledge is very important and I think it's important for two reasons. First of all because it's difficult to imitate because it is tacit so it's not codified. And also it copes very well with the need for secrecy that all Formula 1 teams have. So the fact that Formula One teams seldom patent anything for a fact that they don't have time to patent anything and they don't even have them you know it also doesn't make and also if they patented their solutions everybody will know. So they have to work with secrecy and tacit knowledge in how to do things is basically what drives innovation. Most of the time. This is why the quickest way to get...some type of innovation, some type of knowledge and put processes into one Formula 1 team; is to hire the people that in the companies you are trying to imitate was actually developing that specific process. So this is what creates that kind of you know inter-firm mobility across highly skilled technicians or managers who then bring a set of knowledge that is not codified and that can be extremely useful.

**Author:** So the next bit is prior alliances. You have already mentioned that you know companies tend to form alliance if they already have a history of working together. Can you explain things like breakdown of the relationship between Red Bull and Renault in that regard because they did win four world championships with Renault?

**Interviewee 2:** I think they simply in fact I think things don't explain very well I think the Red Bull did something quite unreasonable to you know put the blame on Renault that quickly. I mean for sure. Renault engine was not delivering what they were expecting but after winning 4 championship I think you can be a little more patient. I think they rushed quickly to the conclusion and ultimately they ruin th relationship there for some... for sack of availability, they will have to keep for another year. So I in fact I don't think there was a very smart move overall. But you know red bull has high ambitions. And last year it was not he was not even competing for a world championship. I'm not talking about winning the world championship but at least competing. So this is the thing, the reason why I did say actually to drop them the bomb and decide to move or at least tried to move to some other producer.

**Author:** And moving on, the next two aspects are proximity to core competence and absorptive capacity. So Mercedes and Williams are in a alliance and all of a sudden Mercedes realizes that the only contribution they had last year during the first half of the season was Williams which was using their own engine. Does that affect the knowledge sharing process in an alliance like that.

**Interviewee 2:** Well usually what happens is that manufacturers, engine manufacturers that are also keen competitors. They don't share their ups, their most updated engine, and some technology with their competitors when they realize that it's a better competitor. I mean Mercedes had an advantage there went way beyond what we Williams have, they have more resources, done an incredible job in their hybrid system. So in the end the official or unofficial voice is that they don't believe they don't deliver the same engine that they have. Or maybe they did unbelievably update as quickly as they would do they're onto you. So that's how you create a slag. But still there are situations in which this mechanism don't play out well or work because for example you have it happened in the past that when Renault was competing with its team and in turn Red Bull win the championship again and again. So it can happen that a customer car wins or among factory happened before it can happen again.

**Author:** And probably that was the reason why Mercedes and Ferrari were unsure about sharing their engine.

**Interviewee 2:** That's a reason I mean Mercedes said a straight no. Ferrari said we happy to sell as long as they agree not to get the engine that we have, the very last season's engine. I mean Ferrari doesn't even sell that engine to a Toro Rosso or a Hass which technically speaking not have the same skills, the same you know technological advancements, as Red Bull. So to be cautious so I think that's the reason.

**Author:** And building on that how much you think your alliance partner's absorptive capacity plays into it. i mean Williams compared to Mercedes is a small team; when you compare the size and budget; so a Mercedes can, I mean one assumes here that they have a lot more technological know how then compared to Williams; especially in the area of hybrid engine which is not an area of expertise for Williams and Williams have always collaborated with engine manufacturers. So what role does absorptive play in such a scenario?

**Interviewee 2:** Well OK. If absorptive capacity... I mean I go back to the original paper of Cohen Levinthal in 1990 on absorptive capacity. For me absorptive capacity is that capacity to absorb knowledge or external knowledge and is created by the prior investments that companies having specific knowledge domain. So say because I invested a lot into understanding how hybrid system works is supposedly I will be better off learning new things about hybrid systems. There's a kind of you know I indulge in edhi effect a little bit but on the other hand it's also what drives understanding and learning.

**Interviewee 2:** So my idea is if there are certain teams that are traditionally much better at developing in certain aspects so Red Bull has always been very good in aerodynamics, Ferrari has always been very good in engines, Mercedes recedes is very good in engines and aerodynamics. So I think there's a there's a kind of you know expectation. So what you know, you know is that you know..well on the one hand you know absorptive capacity allows you to put people...rather than absorptive capacity, we'll talk about learning. So companies try to collaborate to learn something from their partners or at least to obtain the knowledge that they lack to close the gap with competitors. On the other hand absorptive capacity shows that if a company has a long track record on one specific domain it will be better learning in the same domain. So let's say, if, we know that Red Bull Racing has an extraordinary understanding of aerodynamics than what they miss is the engine production. So they will try to pair up with the teams that are very, that can provide them understanding or knowledge or technology on engine mechanics. And I think this is pretty much the reason why certain complimentary synergic alliances are born and why other don't come up, don't get established.

**Author:** Yes that is very interesting you say that the reasons are...so what really decides whether an alliance for knowledge transfer is successful or not. Where you know, For example what is, what is making the Mercedes and William alliance work and why the Renault and Red Bull alliance fault? What is the reason behind the successful knowledge transfer alliance.

**Interviewee 2:** Well I'm not sure there is a knowledge transfer there. I think there was more like an integrative capability. So it’s not that...I mean knowledge transfer means that you know it would mean that let's assume that Mercedes works with Williams So Mercedes transferred the knowledge on engine to Williams and then I would expect next year Williams to build its own engine because they learnt how to build engines. But this doesn't happen. What happens is they simply put together two components they built together and these two components seem to work very well together. Although they're not being designed to work together, they have kind of modular fitting. So I think rather than looking at knowledge transfer here which is I think something that happens more and between perhaps other type of suppliers and not engine suppliers, here it's more like integrative capability. So how comes the same components work very well in some cars and in others they work less well. So in Williams, the engine works extremely well, in Force India, a little less. Main reason is also money and expertise. Williams is one of the most successful teams in Formula One and been there for many years despite being a relatively smaller teams. Let's say they are bigger of the small teams of what we call the garigestas. They normally only do cars for racing, they don't sell other products besides consulting and stuff like that. So I think they are quite good at knowing what you're doing. Force India is a lower limit, lower budget company and lower budget team and they are less experienced, have less talented engineers. Overall they come up with the package that is less profitable, less performative than what Williams can come up with. So I think it's a matter of skills and experience.

**Author:** I'm sorry to interrupt, but it's very interesting you said that knowledge transfer happens in case of other suppliers. So for example let's say Xtract the gearbox supplier. In what sense would they benefit from their alliance with of a Formula 1 constructor?

**Interviewee 2:** Well the alliance with Formula 1 constructor allows them to understand how highly technologically advanced organization works in a highly competitive environment, learns to overcome its challenges. Right so it's a way of learning for example processes, application of components. You basically open a box of one of the most technologically advanced organizations and you are able to read inside this kind of; you know the box and see what's there. And so you learn on the other hand the team can learn something about a specific application of a component. And this will allow them in the future either to vertically integrate or eventually in that specific time to access type of knowledge that is in the field. So to say if a company works with a supplier. The only way you'll have to absorb what your competitor does is either you manage to copy them or you work with a supplier, this company work with in trying to access to the same level of knowledge same level of quality of components that your competitor is using.

**Author:** That's very interesting because when I look at the company of size of Magneti Marelli one of the biggest, you know electronic component manufacturer in the world. They get into alliance with a lot of Formula 1 teams, especially the longstanding alliance with Ferrari. And I am thinking about direction of knowledge flow there. Is flow from Ferrari to Magneti Marelli or the other way around and what role does that directionality play?

**Interviewee 2:** My feeling is that probably Ferrari learns from Magneti Marelli I mean Magneti Marelli are part of the same group, they are part of the Fiat group. So anyway Magneti Marelli learns from Formula One more in terms of you know practices, in terms of and it has an opportunity to invest in a highly competitive environment some type of products. So basically good thing about working with Formula 1 is that you basically can push your technological boundary to the limit and therefore come up with new solutions. Then other industries would be maybe even too much. It's a testing ground for new ideas while at the same time Formula 1 learns something in terms of the specific technology application. You also have to consider a certain components these days have become commodities. So for example the central ECU of Formula 1 car, I think is supplied by McLaren to everybody. And so it's a commodity, so you do not really learn anything because everyone has the same component. It is like tyres, you don't learn anything from tyres because everybody got tyres. That you have because Pirelli supplies for everybody. At best what you learn is you learn how to fit the tyres when you're, in your architecture or you learn you know how which tyre works best. In depending on what setup you have or what kind of environment in the race there is but it's just a commodity, you get it because you know because everybody does. And then there are certain components you like or core components which are the ones where actually you have a massive impact on performance. In other cases you only have an impact on performance on negative cases.

**Interviewee 2:** So to say when basically the component breaks down so car doesn't work but you don't have an advantage if it works. Or the advantage is minimal so in those cases the logic of convenience is what drives the relationship.

**Author:** Very interesting. So when you think about Formula 1 and knowledge transfer, which industry do you think Formula 1 can contribute to , which industry do you think, in your opinion can learn from Formula 1 or is already in the process of profiting from the technical expertise that Formula 1 has to offer.

**Interviewee 2:** Well Formula 1 has a clear connection to automotive which has always been because the owners of majority of the teams are the automotive companies or their...like I always say it's, Formula 1 is like the Big Brother of a Big Brother show of an R&D lab. So basically you take an R&D lab and you create a show around this. You basically make some money out of the efforts that your army of engineers are doing. So majority of formula 1 teams have the imperative duty to passs or to develop valuable knowledge for the automotive industry. However there have been application to many other fields like hospitals or health care. Defense, transportation, sports industries, aerospace, satellite communication, big data communication, boat design. So there's plenty of application technology wise. I think we're just scraping the surface of the things that formula one can do in terms of developing technology. In terms of developing practices, I think its application is almost universal because the kind of pressure that the go through with the kind of dynamics they go through they are second to nobody. And this is why you know people, colleagues of mine, like Professor Mark Jenkins or others have been able to develop such compelling lessons for a manager from any type of industry. So especially fast paced industry, you can find a lot of similarities or at least you know there are broader managerial lessons you can learn. So I think that applicability is very very broad with a let's say un primary role of automotive

**Author:** So the final question is what factor or dimension of knowledge would you classify as being a very critical role in the success of these alliances.

**Interviewee 2:** So depends what you mean success of alliances. So you mean success for the Formula One team or success for the component producer. Because I think there are at least two type of alliances here; the alliances that Formula 1 team creates with their suppliers and their partners in that contributed to racing. So the customer in this case is the Formula 1 team and a provider of knowledge is most of the time and other is component producer or another Formula 1 team that provides the engine or other parts of the car. In that case the measure of performance is how well the formula 1 team is performing in the races. There is another measure of knowledge transfer, what in my paper on industrial corporate change I call the external knowledge transfer which means the fact that you bring knowledge from Formula One domain, may this be technical knowledge, may this be simple knowledge, simply process knowledge or you know practices best practices to other domains. In this case the measure of performance is how fruitful this knowledge transfer, these new insights that you are suggesting that a formula 1 teams to the external partner are for a business of the external partner. Often new technology or a partner.

**Interviewee 2:** This is totally idiosyncratic to the task and you know I'm today at the company and how they work together. I think it depends of course it depends on you. But I think there are certain domains where Formula 1 has an expertise that is stronger. Like simulations or any kind, from CFD to Monte Carlo simulations for the races. Improvement of design engineering so how to improve the design of an object to for a specific purpose. And the third is management of complexity. So in terms of management practices how do you take decisions in situations where you have multiple stimuli and multiple sources of information? And you perhaps have a limited amount of time element amount of cognitive resources to provide a response. I think Formula 1 teams are very good at making the decision, making extremely linear and synthetic and effective. This is another field in which they, they can give a major contribution. But this is not it, Of course they can do much better than that.

**Author**: You have to make a distinction between the knowledge transfer that is focused on racing success and knowledge transfer which you classified as external knowledge transfer.

**Interviewee 2**: Exactly.

**Author:** Thank you, those are all the questions that I had in mind.

**Interviewee 2:** You are welcome.

## Interviewee 3

Date: 06/04/2016

Interviewee 3 is Professor of Engines and Energy System and based at a highly regarded British university. He has an extensive experience of working in industry, including Formula 1 constructors and engine manufacturers and other motorsports, such as Indy Car in the US. Much of the interviewee's research has been collaborative with universities and industry and gives him a unique vantage point on the subject of (tacit) knowledge transfer in Formula 1.

The interview involved discussion of the interviewee's work experience at various firms, in Formula 1 and automotive industry and as such included mention of information sensitive for these firms. The interviewee wished for the discussion to remain confidential. Therefore, author has withhold the publication of the transcript.

# Appendix 8 Journal Publication Based on the Thesis

## Tutors and gatekeepers in sustainability MOOCS

D Mishra, S Cayzer, and T Madden

On the Horizon 25 (1): 45-59

### Introduction

The call for papers for this special issue challenges us to consider whether digital pedagogies are *"supportive of sustainability or perpetuators of unsustainability"*. Since Foster (2008) defines sustainable development as *"a social learning process to improve the human condition"* it would therefore seem appropriate to consider whether digital pedagogies can enable social learning. Our focus here is the use of online platforms, specifically MOOCs.

MOOCs (Massive Open Online Courses) are sometimes credited with the potential to revolutionize distributed learning. Practices such as learner generated resources, system thinking and citizenship education, are characteristic of so-called *connectivist MOOCs, or 'cMOOCs'*. In such MOOCs, it might be that the educator could take the role of facilitator or even absent themselves entirely from the learning process. At the other end of this continuum in MOOC categorisation is the 'xMOOC' where pedagogy is not dependent on learner contact and is driven by tutors via lectures and automated assessment (Bayne & Ross, 2014). Larger 'traditional' distance learning courses could potentially be included in such a definition. Increasingly, however these distinctions are becoming irrelevant. Most MOOCs cannot be neatly arranged into these two categories and often show contradictory participation patterns (Kop, 2011).

In this paper we examine the extent to which MOOCs enable social learning. We use Social Network Analysis (SNA) to explore the nature of interaction between participants in two different MOOCs, particularly the role of tutors in mediating such interactions. We find that tutors, playing the role of facilitator and educator in the MOOC, can and do take a central role in some cases. However, in other cases the removal of tutors has little effect, suggesting that different modes of learning are possible in a MOOC community. We see participants playing central role in the network as 'gatekeepers'; influencing network learning, learning driven by the participants via conversations among themselves and information flow. The implication is that digital pedagogies, when structured correctly, can enable social learning and thus support education for sustainability.

Related Work

McAuley et al. (2010) define MOOCs as "*…a significant departure from the cliché "ivory towers" of traditional brick and mortar universities, the "walled gardens" of conventional learning management systems…*" Some authors (Jacobs, 2013; Hew & Cheung, 2014) argue that MOOCs offer a model of democratisation in higher education: courses available to the greatest number of people possible with the lowest barrier to participation. MOOCs differ from traditional classroom learning in their scale, pedagogy, and reach (Yuan & Powell, 2013). This has potential repercussions for higher education and its traditional practices (Gillani & Eynon, 2014; Gašević et al, 2014). Sinha (2014) highlights how MOOCs are prompting participants to rethink learning and it has also been suggested that the real potential is in the new knowledge created through student interaction within MOOCs (Gillani & Eynon, 2014). Thus, the traditional roles of student and teacher are challenged (Koutropoulos et al, 2012; Rodriguez, 2013); for instance, in connectivist-type MOOCs, the educator could take the role of facilitator or even absent themselves entirely from the learning process (Kop, 2011). This approach is not, of course, unique to MOOCs, but it is possible that the scale and reach of MOOCs allow these learning networks to be qualitatively different to those found in classroom environments.

Social Network Analysis (SNA) is a key tool to understand patterns of interaction in education (de Laat et al 2007). SNA has been used to perform quantitative comparisons between different communities and courses (Shen et al 2008). The structure of the network can be pedagogically important: Reuven et al 2003 (quoted by de Laat et al 2007) have found that critical thinking was enhanced in a structured network (rather than an unstructured forum).

In the context of digital pedagogy, there are a number of relevant mathematical measures, or *metrics*. Simple metrics include the number of participants (*nodes*) and interactions (*links,* though also known as *edges* in the literature) in a network. These metrics give a sense of scale, which is usually of a different order of magnitude in a MOOC compared with a traditional classroom environment, or, indeed many online courses. MOOCs tend to have low participation as a percentage of total enrolments, with completion rates around 15% (Jordan, 2015). In addition, the vast majority of MOOC participants tend to 'lurk', that is, operate in read-only mode; Breslow et al (2013) found over 90% of participants were lurkers. Thus, the **density** (the percentage of all possible links present) is expected to be low. This gives an initial picture of participation**.** However, as Lipponen et al (2003) point out, high density may be due to one dominant individual. In this way, a highly-active teacher's presence may affect the density of a network disproportionately (Martinez et al 2003).

Toikkanen & Lipponen (2011) assert that density is "unrelated to quality or meaningfulness" of online learning. If this is the case then perhaps we need a node-centric metric such as **degree** (Rabbany et al 2014; Russo & Koesten 2005) which refers to the number (or relative proportion) of links to a node. The degree can be weighted (e.g. by the number of times these nodes have interacted). **High degree** denotes a node that is highly connected in the network and potentially highly influential; **low degree** denotes a node that is on the periphery (Wasserman & Faust, 1994), thus SNA can be used to identify isolated participants (Reffay & Chanier 2003). It is common to measure **average degree** over a network

**Betweenness centrality** is a measure which incorporates the importance of nodes as interconnectors. It is measured by counting the number of shortest paths which pass through this node. This number is divided by the total **number of shortest paths** in the network to give the betweenness metric. A node with high betweenness has a large influence on the transfer of items through the network. However this metric is not necessarily correlated with the participants' subjective experience of learning (Toikkanen & Lipponen 2011) nor to course grades (Cho et al 2007).

**Average path length** shows how closely connected nodes are; however this metric can only consider finite path lengths i.e. connected nodes. **Diameter** is the longest of these shortest paths. A large diameter implies a potentially loosely connected community; a small diameter may be a very densely connected community, or one in which few connections are present (most nodes unconnected or in small clusters).

These possibilities can be teased apart by looking at the *clustering* of the graph. Connected nodes tend to form in clusters, which may be weakly or strongly connected. **Weakly connected clusters** are those in which every node is connected to every other, directly or indirectly through other nodes in the cluster. It is common for the entire graph, with the exception of isolated nodes, to form a single weakly connected cluster. However, participants can be originators (**in-degree**) and/or recipients (**out-degree**) of connections: for example, posting or receiving replies on a discussion. When this link direction is taken into account, **strongly connected clusters** are those where every node has at least one in-link and at least one out-link to some other node in the cluster (not necessarily the same node). A strongly connected cluster suggests a more conversational nature of interaction.

**Modularity** is the tendency to form sub-communities. More precisely, modularity compares links <u>within</u> clusters against links <u>between</u> clusters. The result is calculated as a scalar with +1 representing perfect modularity (ie all links <u>within</u> and no links <u>between</u> clusters). The algorithm proposed by Blondel et al (2008) starts with individual nodes (i.e. clusters of size 1) and then performs a hill climbing search, clustering nodes one by one until modularity can no longer be increased by the addition of one more node. The algorithm repeats on the clusters produced by the first pass, and so the process repeats until a local maximum is reached. A modular structure might result in deeper, or perhaps just more fragmented, community discussion. Toikkanen & Lipponen (2011) find that communities with low modularity and few clusters are conducive to learning, at least according to the learner's subjective experience.

These SNA metrics will be used to build up a rich picture of network structure with and without tutors, and to relate this structure to pedagogic outcomes.

Methods

We focus on the 'Sustainability for Professionals' MOOC delivered by the University of Bath on the FutureLearn platform which hosts the 'Inside Cancer' MOOC, also from Bath. 'Sustainability for Professionals' tends towards being pedagogically connectivist, with 'Inside Cancer' being more traditional and instructor led. To be more precise, 'Sustainability for Professionals" was designed[1] along the following principles:

- The course is designed to encourage conversation and connection between participants
- The course makes use of FutureLearn facilities to encourage and maintain connections (e.g. like, follow).
- There are discussions of the form "Share your experience of [X]"; thus, sustainability decision-making is framed as a learning process.
- The course uses the diversity of perspectives to bring context to the topic under discussion. As Siemens (2005) notes: *"While there is a right answer now [here], it may be wrong tomorrow [elsewhere] due to alterations in the information climate affecting the decision"* (alternatives in square brackets our

[1] a lead designer, Madden, is an author on this paper

additions).

These MOOCs were chosen because they differ in staffing, pedagogy, and subject matter. This helps us to juxtapose how different approaches can lead to different learning patterns.

The FutureLearn platform provides a dataset containing comments posted by the participants and tutors during the course. These comments are time stamped, with each commentator and comment being assigned a unique identification number. Comments may be either directly associated with course content, or may be a response to another user's comment.

For our analysis we used Gephi, a popular industry standard open source network analysis and visualization toolkit (Jacomy et al., 2014; Burns, 2012).

The definition of nodes and links are as follows:

- A *node* represents a participant who has posted at least one comment (we also use the term 'active participant'). This is not the same as FutureLearn's definition of an '*active learner*' – a participant who has completed at least one section of the course. In general, only a proportion of active learners post a comment and become active participants. This proportion is around 60% for the Sustainability MOOC and 40% for the Inside Cancer MOOC.
- A *link* represents a response to a comment. The FutureLearn dataset does not support hierarchical responses, so the recipient node is taken to be the owner of the original comment and not any intervening response.
- *Link weight* is the number of interactions between 2 nodes (participants). Directed links are permitted and recorded; the results reported here use directed links.

We coded a data transformation (Appendix I), to create nodes and links for Gephi from the FutureLearn dataset

Table 1 shows number of nodes and links for each run of the courses.

**Table 1: Statistics for different runs of the "Sustainability for Professionals" and "Insider Cancer" MOOCs.**

| MOOC | Sustainability March 2014 | Sustainability January 2015 | Sustainability August 2015 | Cancer January 2014 | Cancer September 2014 | Cancer March 2015 |
|---|---|---|---|---|---|---|
| Nodes | 962 | 1109 | 1177 | 1512 | 1099 | 1069 |
| Links | 2312 | 2279 | 1822 | 1215 | 1255 | 1141 |

These files were imported into Gephi, and those metrics held to be most useful to investigate the networks (see Table 2) were calculated to create the final dataset containing values for each node and the graph as a whole

**Table 2: Metrics used for SNA analysis of the MOOCs**

| *Metric* | *How Calculated* |
|---|---|
| ***Nodes (Participants)*** | Simple count |
| ***Links (Interaction among participants)*** | Simple count |
| ***Network Diameter*** | Longest finite optimal path between nodes using undirected links |
| ***Graph Density*** | Fraction of all possible undirected links present |
| ***Modularity*** | Calculated using Gephi algorithm, based on Blondel et al (2008) |
| ***Weakly Connected*** | Minimum number of clusters in which each node is reachable from every other node along undirected links |
| ***Strongly Connected*** | Minimum number of clusters in which each node is reachable from every other node along directed links |
| ***Average Degree*** | Average number of undirected, unweighted links per node |
| ***Average Weighted Degree*** | Average sum of weights on undirected links per node |

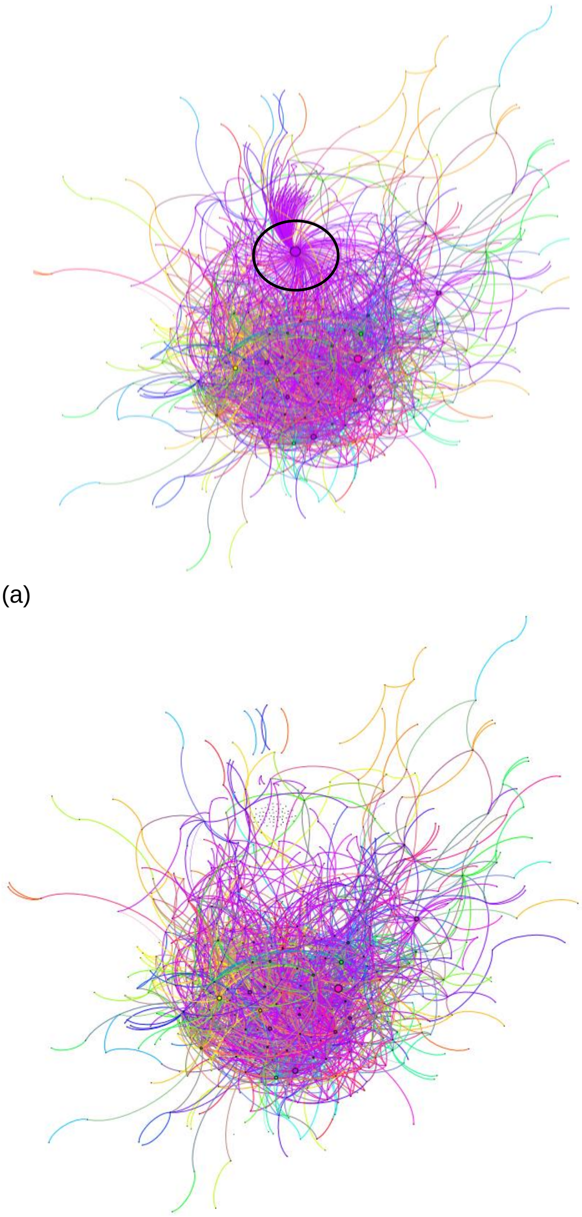
| | |
|---|---|
| ***Average Path Length*** | Average path length (along undirected links) between all connected nodes |
| ***Number of Shortest Paths*** | Number of optimal routes found between nodes |

Interviews with Tutors

In addition to SNA, structured interviews were carried out with the lead tutors on the two MOOCs to contextualise the network analysis and discuss the metrics. The interview questionnaire is in Appendix II. The interviews highlight the approach of tutors to the online learning environment and their expectations (or lack of) concerning network learning. The tutors also remark on differences between a traditional pedagogic environment, such as university classroom, and a MOOC.

The interviews highlighted the tutors' approach to the MOOC and helped contextualise the SNA findings within the broader framework of pedagogy.

Results



(a) (b)

**Figure 1 Sustainability March 14 Network Graph with (a) and without (b) Tutors. One of the tutor nodes is circled**

**on the left hand picture. Node size and colour is based on Betweenness Centrality**

Figure 1 illustrates the effect of removing tutors from a network. A number of well-connected nodes (including the one circled in the picture) have been removed; and yet the network still appears richly connected. Of course, this is only a visual impression and a deeper inspection can be achieved through the examination of SNA metrics as shown in table 3.

**Table 3: Metric Table. Figures in brackets are metric value of the network without tutors. Where no figure is given, the removal of tutors had a negligible effect on the value of the metric.**

| ***MOOC*** | ***Sustainability March 2014*** | ***Sustainability January 2015*** | ***Sustainability August 2015*** | ***Cancer January 2014*** | ***Cancer September 2014*** | ***Cancer March 2015*** |
|---|---|---|---|---|---|---|
| ***Nodes (Participants)*** | 962 (955) | 1109 (1103) | 1177(1172) | 1512 (1503) | 1099 (1093) | 1069 (1063) |
| ***Links (Interaction among participants)*** | 2312 (1959) | 2279 (2165) | 1822 (1715) | 1215 (1020) | 1255 (1126) | 1141 (1075) |
| ***Network Diameter*** | 10 | 12 | 12 | 14 (12) | 11 | 11 |
| ***Graph Density*** | 0.003 (0.002) | 0.002 | 0.001 | 0.001 (0) | 0.001 | 0.001 |
| ***Modularity*** | 0.305 (0.338) | 0.373 (0.367) | 0.401 (0.42) | 0.501 (0.542) | 0.401 (0.422) | 0.402 (0.405) |
| ***Weakly Connected*** | 356 (423) | 470 (480) | 586 (589) | 972 (1008) | 664 (669) | 669 (673) |
| ***Strongly Connected*** | 764 (786) | 887 (891) | 987 (985) | 1435 (1450) | 1011 (1008) | 976 (973) |
| ***Average Degree*** | 2.403 (2.051) | 2.055 (1.963) | 1.548 (1.463) | 0.804 (0.679) | 1.142 (1.03) | 1.067 (1.011) |
| ***Average Weighted Degree*** | 3 (2.53) | 2.705 (2.596) | 2.038 (1.933) | 0.997 (0.844) | 1.669 (1.525) | 1.843 (1.751) |
| ***Average Clustering Coefficients*** | 0.048 (0.031) | 0.029 (0.028) | 0.024 (0.023) | 0.01 (0.008) | 0.024 | 0.023 |
| ***Average Path Length*** | 4.155 (3.922) | 4.189 (4.157) | 4.61 (4.644) | 4.766 ( 4.58) | 3.719 (3.703) | 3.907 (3.937) |
| ***Number of Shortest Paths*** | 128329 (95859) | 150918 (141036) | 115241 (112381) | 54160 (37074) | 41945 (38210) | 42523 (39890) |

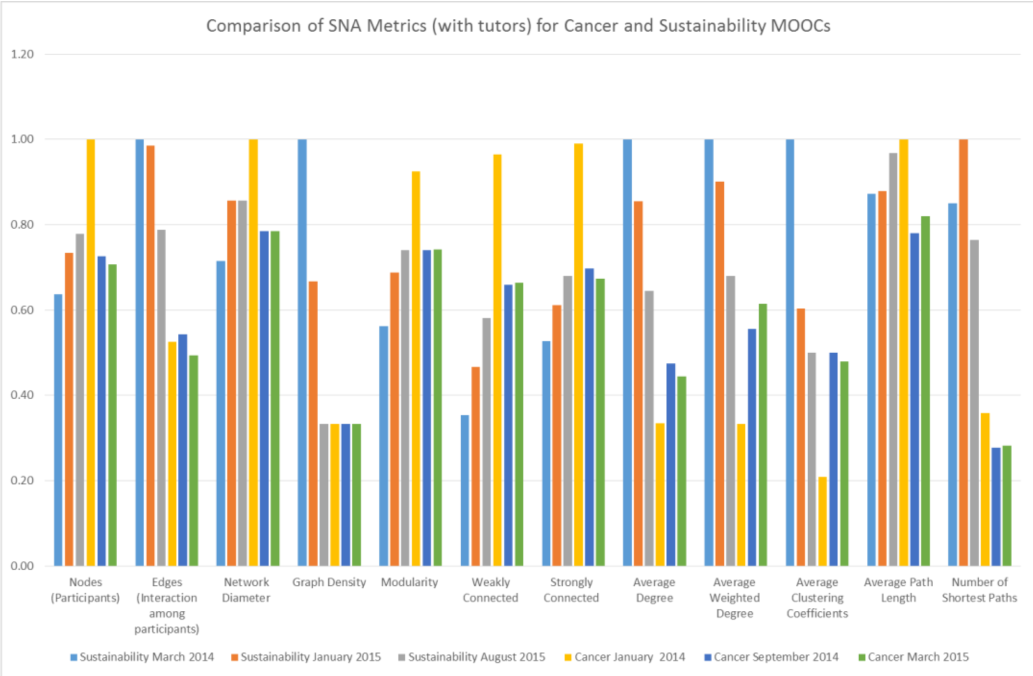



**Fig 2: Comparison of SNA metrics for Sustainability (first three columns in each group) and Cancer (final 3 columns in each group) MOOCs. The metrics are normalized against the maximum for that particular metric.**

Table 3 presents the summary results for the SNA metrics considered. Figure 2 presents the data in a relative form (normalised against the maximum value for that metric across all six MOOC runs). The number of active participants (nodes) increases for subsequent runs of the Sustainability MOOC but with the number of connections (links) decreasing. A contrasting effect occurs for the Cancer MOOC, with the number of nodes decreasing and the link numbers holding steady. Another contrast is shown for network diameter, with the value for the Sustainability MOOC increasing and that for the Cancer MOOC decreasing. The average path length shows a similar pattern.

The density for these MOOCs tends to be low with Sustainability having a higher density then Cancer. In case of degree, we observed that the Sustainability MOOCs had higher average and weighted out-degree than Cancer MOOCs. Again, subsequent runs appeared to have opposite effects, with degree increasing in Cancer MOOC but decreasing in the Sustainability MOOC.

Looking at connected components we found two distinct trends. First, in both courses, there are almost twice as many strongly connected components as weakly connected components. Second, runs of the Cancer MOOC have higher number of connected components, both weakly and strongly. This difference reduces with subsequent runs to the extent that it is barely noticeable on the third run. Modularity also displays the same trend. The first run of the Cancer MOOC has a much higher modularity compared to its Sustainability counterpart, but this difference disappears by the third run of the MOOC. The clustering coefficient exhibits the same trend as modularity but in reverse (with values increasing rather than decreasing and vice versa).

Overall, the metrics appear to be converging over repeated runs with two exceptions: number of edges and number of shortest paths. In both cases Sustainability is consistently and appreciably higher than the Cancer metric; the latter showing no sign of increasing. This is evidence of some persistent difference between the MOOCs. Further evidence is given by a higher proportion of nodes with high betweenness centrality in the Sustainability MOOC (figure 3).

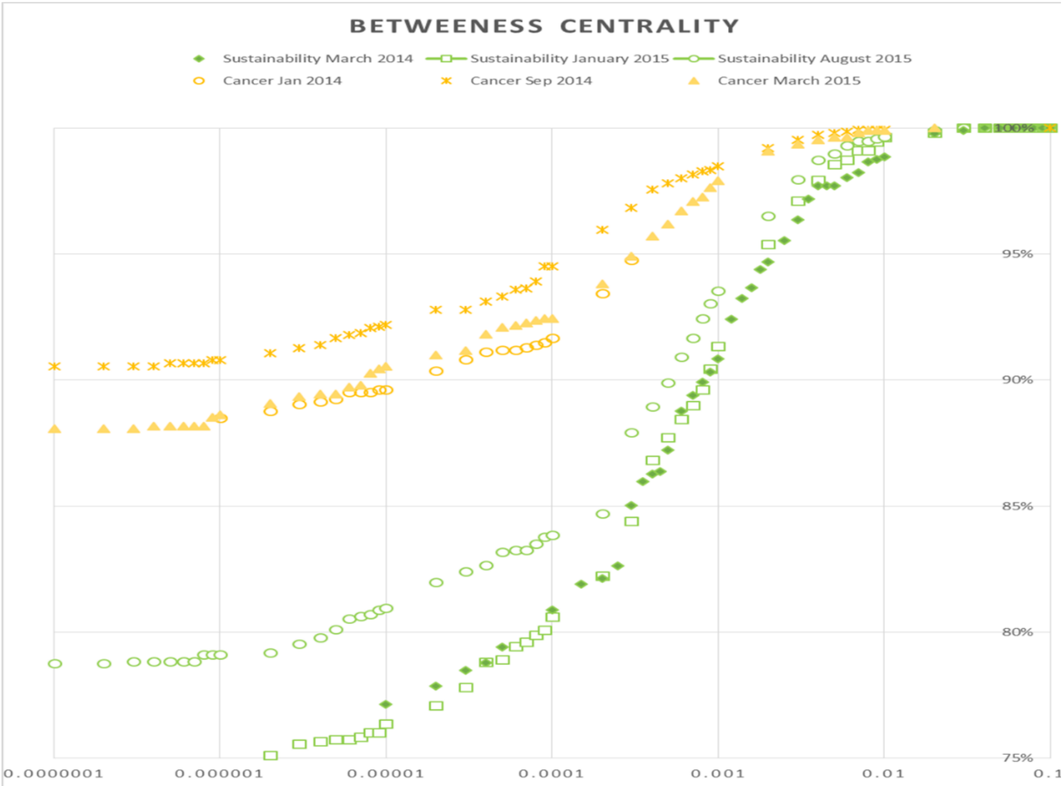



**Figure 3. Cumulative distribution of betweenness centrality for three runs of the Sustainability and Cancer MOOCs. Betweenness centrality is plotted on a log scale (unitless), and the graph is expanded to show the top 25% participants ranked by betweenness centrality.**

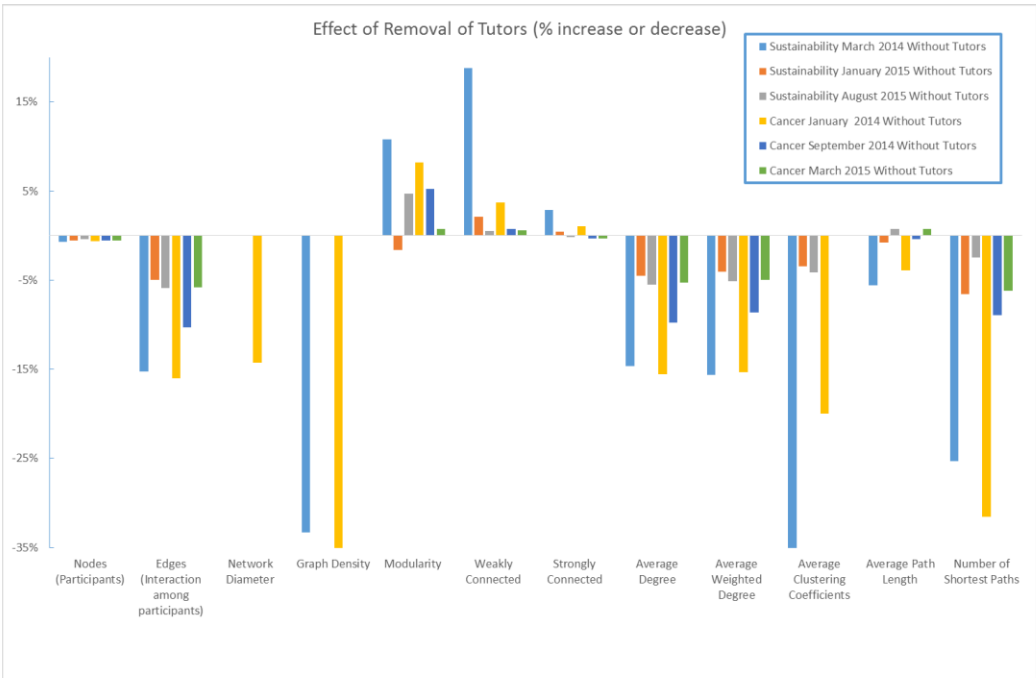



**Figure 4. Effect of removal of tutors (% increase or decrease). The bars are arranged as for figure 2. The bar for the density in the first run of the Cancer MOOC has been cropped from -100%.**

As one would expect, the removal of tutor nodes (fig 4) has a negligible effect on the number of nodes (less than 1%), but the effect on links is more marked, particularly on the first run. The removal of tutors also appears to have little effect on overall density; we observed an appreciable effect only in the first run of each MOOC where removal of tutors from the network resulted in more than 33% drop in density. Removal of tutors increases modularity and number of connected components, but decreases all other metrics.

In general, removal of tutors appears to have the most effect on network metrics in the first run of each course.

Interviews with Lead Tutors

The lead tutor for the Cancer MOOC remarked on the nature of interaction among learners and how the level of engagement was "*surprising*". They also commented on the role of tutor in *clarifying* and *verifying* information posted by learners. The Cancer MOOC is part of a content-driven discipline and needs tutor intervention on matters of technical knowledge and veracity of information within the network. The tutor felt that the MOOC offers more robust engagement for students in terms of involvement of patients, experts, and consultants when compared to the traditional classroom environment. The tutor also highlighted a different approach to aid student learning in the MOOC with focus on *end of the week wrap-ups* to assist student learning.

The lead tutor for the Sustainability MOOC pointed to the design of the course as a critical factor for an online learning environment and how it leads to greater participation. In case of Sustainability MOOC, the lead tutor already had experience of distance learning programmes and found that helpful in delivery of the MOOC. Though they thought that the MOOC is similar to online distance learning programmes, the MOOC generated more positive feedback and they thought it to be more engaging and enjoyable for the tutors. The lead tutor also felt that MOOCs appeared to have more potential for network learning compared to traditional distance learning as students involvement appeared to be increased. MOOC learners displayed a distinct set of motivations compared to traditional pedagogic environment learners, such as university students. The lead tutor added that students in university may be more driven by "*value for money"* aspect of the course whereas MOOC participants with their different backgrounds and professions are more interested in learning for the sake of it. The lead tutor also pointed out how conversations in MOOCs are initiated by highly confident people before spreading through the network.

Discussion

Social Network Analysis (SNA) is a key tool to understand interactions in an online environment (de Laat et al 2007) and allows quantitative comparison between different networks and thus between courses (Shen et al 2008). The structure of the network can be pedagogically important: Reuven et al 2003 (quoted by de Laat et al 2007) have found that critical thinking was enhanced in a structured network (rather than an unstructured forum). Table 5 shows a comparison between sustainability MOOC and a traditional pedagogic environment course.

**Table 4: Comparison between a traditional pedagogic environment course (left hand column: data taken from Palazuelos et al 2013) and the Sustainability and Cancer MOOCs (all three runs)**

| Characteristic | Introduction to Multimedia Methods | Making an Impact: Sustainability for Professionals | Inside Cancer |
|---|---|---|---|
| Size | ~70 | 962 - 1177 | 1069-1512 |
| Density | 0.05 - 0.07 | 0.001 – 0.003 | 0.001 |
| Average degree | 1 - 2 | 0.5 – 1.5 | 0.8 – 1.1 |
| Diameter | 11-19 | 10-12 | 11-14 |
| Components | 1-3 | 356 - 586 | 664-972 |
| Average size of component | 20-70 | 2-3<br>largest component: 550-650 nodes | 1-2<br>Largest component: 350 – 550 nodes |

Although the number of participants did vary between the MOOCs, and between the individual runs, the number of active nodes was between 962 and 1512, thus allowing comparison between the datasets.

Density for these MOOCs tend to be low, perhaps because a majority of MOOC participants are predominantly in a 'read only' mode. Density can be problematic as the presence of even one dominant node can greatly skew its value. We observed that trend only in the first runs of the Sustainability and Cancer MOOCs (this aligns with the conclusions of Martinez et al 2003.).

Average degree and diameter are somewhat reduced in MOOCs; however this difference is small in comparison to the explosive growth of clusters, many of which are in fact isolated nodes. This suggests that the connectivity in MOOCs is worth exploring further.

One common finding is that the Sustainability MOOC is better connected that the Cancer MOOC, with higher values for links, cluster size and number of shortest paths. Toikkanen & Lipponen (2011) have shown in their paper that students with better network connectivity have a more meaningful learning experience, at least according to their subjective judgement.

Betweenness centrality presents an interesting picture. Frequency distribution (figure 4) curves suggest that the Sustainability MOOC nodes usually have a wider distribution and higher values for the betweenness centrality metric. For example, almost 10% of the Sustainability nodes have betweenness of 0.001 or higher, whereas in Cancer only the top 2% of nodes are this well connected. This suggests that the Sustainability MOOC design has had a tangible effect on *network learning*, which we define *as the learning driven by the participants via conversations among themselves*. In network learning; participants acting as information brokers attract other participants based on their reputation and are hubs for flow of information flow (Kop, 2012). This phenomena is particularly relevant for sustainability. Sustainability, perhaps more than any other academic field, is most relevant to daily life of citizens. Citizens not only need to be aware of sustainability as a concept but also be taking active part in promoting sustainable practices to ensure sustainable development. For this to happen, sustainability conversations need to spread via mediums other than traditional pedagogical environments such as classrooms and university campuses, and to this end, network learning is conducive. Driven by participants, a network learning environment can facilitate wide penetration of sustainability awareness.

The lead tutor interviews confirm these intuitions; the Cancer MOOC is more traditional in its structure and involves tutor involvement on technical subject matter. In the case of the Sustainability MOOC, the lead tutor remarked on how network learning was facilitated via the design of the course. This is also highlighted in literature: Bayne and Ross (2014) remark on how the discipline and related practices influence the pedagogical approach to MOOCs

On subsequent runs of the MOOC, they become more similar in terms of modularity, connected components and degree. However, the number of shortest paths is still appreciably higher in the Sustainability MOOC. A common finding was that the effect of tutor node removal was ameliorated in subsequent runs. Particularly in the case of clustering, modularity and connected components, tutor node removal goes from having a very strong effect to an almost negligible effect. This suggests that both MOOCs are adapting to a network learning mode. This ability of a MOOC to adapt and encourage network learning even when the course is not specifically designed to do so stands out in our study.

Studies done using SNA (Xie et al., 2011) have described the role of *gatekeepers*, who themselves resist external influence, are committed to spreading their point of view, and when they reach an inflection point, their 'followers' adapt their point of view. Boyd et al. (2010) describe how these gatekeepers filter the information and resources that reach other participants within the network. We suggest that this description is apt for our identified participants with high centrality. While of course all participants may access any comment or response, in practice gatekeepers are critical nodes in the network around which other nodes congregate. Removing these nodes from the network will not only eliminate certain information channels but also remove network connection for a vast number of nodes. However, these gatekeepers would not have responsibility to *validate* the information that they feed into the network as a tutor or information gatherer might. This is where digital pedagogies adapt a contrasting approach to that of traditional learning environments.

However, this does not mean that tutors are *not essential* to such a learning environment. Tutors play an indispensable role in delivery of the course and when approached by participants, they can validate the information that is being filtered via the gatekeepers. Tutors also play the role of '*emotionally engaged* enthusiast' (Ferguson & Whitelock 2014) encouraging learners. Tutors' limited role in initiating conversations within the network is due, in part, to the design and content of the courses and composition of the network participants. A MOOC designed for a discipline that focuses on professionals (Sustainability) will encourage network learning with minimum input from tutors, whereas a MOOC designed in a discipline with highly technical details with a focus on experts and students in the field (Cancer) will behave differently, and interactions within such a network will not be on a similar scale as can be seen in table 3. Participation, as shown by number of links, in the Sustainability MOOC is greater than in the Cancer MOOC. The importance of design is highlighted in the interviews with the tutors as well.

The MOOC networks under study differ depending on the subject matter and yet show a tendency to converge somewhat. As shown in our analysis, most metrics tend to similar values with each subsequent run. MOOCs offer a network learning approach based on connection, communication, and collaboration. Participants build connections and communities leading to collaborations and information flows. The role of participants, as shown in our analysis, is critical and in contrast with traditional pedagogies, it is the participants, especially those who act as gatekeepers that direct the learning process and access to resources.

This implies a different type of learning is possible in a MOOC community where the network of learners, instead of the tutor, facilitate learning. The role of the tutor in such a case is limited to the delivery of the '*lecture*' and participants learn via network learning where gatekeepers act as hubs for information flow and greatly influence the network.

Our analysis shows how pedagogically connectivist-type MOOCs can play a constructive role in sustainability. Sustainability courses that are *designed* and *delivered* in a MOOC environment can lead to network learning with knowledge sharing and conversations being driven by participations. Participations in such MOOCs tend to form communities with certain individuals playing the role of gatekeepers. As our analysis highlighted, these gatekeepers are distinct from tutors who play a limited role in driving the conversation. This type of 'network learning' where participants take a leading role has implications for sustainability pedagogies.

## Limitations and Future Implications

Our study is based on analysis of two MOOCs, Sustainability for Professionals and Inside Cancer, run by the University of Bath. We analysed three runs of each course and thus limited in sample size. Our analysis was not carried out in a *controlled environment,* which may limit its generalizability. The findings therefore should not be taken to describe all MOOCs, but rather describe potential outcomes which can be facilitated by appropriate course design. The gatekeeper role described and demonstrated will not necessarily be the case for other MOOCs, even those designed in a pedagogically connectivist manner. Platforms for MOOCs represent another limitation to our analysis. We made use of FutureLearn platform which is one of many platforms available for MOOCs and it is possible that different platforms will have different effects on network learning.

On limitation of our study is that we did not track other connections between learners, such as 'like' or 'follow', preferring to focus on the connections formed by responses, which we assume involve more cognitive effort. FutureLearn does provide some of this data so it would be possible to augment our analysis in future work. Another limitation is that we did not interact with participants after they had finished the course. It would be useful to interview students on their experience of the MOOC and how it facilitates/obfuscates the learning process.

There is much work to be done to elaborate on the role of gatekeepers and their motivations with a focus on how they affect social learning. A combination of mathematical analysis, observational studies, learning interventions and other methods will be needed to shed more light on the nature of social learning for sustainability in a MOOC environment.

## Conclusion

Our study has implications for sustainability education. Our question was the extent to which MOOCs enable social learning. We used social network analysis to explore the nature of interaction between learners in a MOOC, particularly the role of the tutors in mediating such interactions. We found that tutors can and do take a central role in early runs of the MOOC – however, with the subsequent runs the removal of tutor nodes has little effect, suggesting that different modes of learning driven by participants are possible in a MOOC community. We postulate that in such a network 'gatekeepers' are critical for information flow. In such a network, the tutors can focus on course delivery and verification rather than acting as connectivity hubs. We have shown that two different MOOCs adapt to this pattern to some extent. However differences persist, and we conclude that appropriate digital pedagogical design facilitates social learning in MOOCs and hence education for sustainability.

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Ethics Statement

We have an agreement with FutureLearn that we can use anonymous data for research purposes. We have validated that the data we hold is sufficient for social network analysis. For effective analysis, the data should be pseudonymous; that is, any individual is unambiguously identified. FutureLearn provides dataset with a single unique identifier (e.g. ‘Participant523’).

Given the use of pseudonymous data to present our findings, it is not envisaged that the use of these findings will have any ethically problematic impacts (for example to the reputation of individuals)

We comply with the Data Protection Act, and in accordance with the University’s guidance we use data only within the terms of the FutureLearn licence. For example, we have not sent any mass emails to course participants using the collected emails. We can communicate to participants where required through blogs, Twitter and through approved FutureLearn mechanisms e.g. course mailings.

Regarding tutor interview data, lead tutors were given interview transcripts for approval and consent before publication of these interviews or any excerpts therein. Consent has been recorded.

Research data management and archiving will be the responsibility of the principal investigator (PI). We will work with e-learning to secure archiving of the data generated during this project. All data collected will be kept securely, in accordance with the University's standard practices.

Appendix I

## Python Code

```
import csv
import collections
import argparse

parser = argparse.ArgumentParser(description='Restructure MOOC CSV.')
parser.add_argument('input_csv', type=open)
args = parser.parse_args()

data_in = {}
with args.input_csv as csvin:
    reader = csv.reader(csvin)
    next(reader)  # skip titles
    for cid, author_id, parent_cid in reader:
        data_in[cid] = (author_id, parent_cid.strip())

data_out = collections.defaultdict(int)
for source_author_id, parent_cid in data_in.values():
    if len(parent_cid) > 0:
        data_out[(source_author_id, data_in[parent_cid][0])] += 1

with open('output.csv', 'w') as csvout:
    writer = csv.writer(csvout)
    writer.writerow(['source', 'target', 'weight'])
    for k, v in data_out.items():
        writer.writerow(list(k) + [v])
```

Appendix II

## Interview Questionnaire

- How would you describe your role in the MOOC?
    - (Follow up) Does your role in the MOOC differ from your role in the classroom?
- How would you describe the extent of your involvement in the community of students?
    - (Follow up) Did you find your involvement levels changing with the progression of the course?
    - (2nd Follow up) How does it differ from the traditional classroom environment?
- Did you take on the same role in each run of the course?
    - (Follow up) If yes, why? Does it differ from the classroom?
    - (Follow up) If no, why?
- How would you describe the network learning and involvement of the participants?
    - (Follow up) Did you find the levels of participation changing with the course progression?
    - (2nd Follow up) Does this stand in contrast with the classroom setting?
- What were your expectations regarding student participation and network learning before the course commenced?

- (Follow up) Did these expectations change with the subsequent runs of the course?
- (2nd Follow up) If yes, why?

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